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Maturing Weapon Systems for Improved Availability at Lower Costs

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Library of Congress Cataloging in Publication Data

Maturing weapon systems for improved availability at lower costs /
John Dumond ... [et al.].
p. cm.
"Prepared for the United States Army."
"MR-338-A."
Includes bibliographical references.
ISBN 0-8330-1513-3
1. United States. Army—Weapons systems—Maintenance and repair. 2. Management information systems. I. Dumond, John, 1945– . II. United States. Army.
UF503.M38 1994
355.8'2'0288—dc20 94-6662
CIP

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Published 1994 by RAND
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Preface

The report advocates a promising approach to reducing the reliability and maintainability burden associated with advanced weapon systems such as the Apache helicopter and the M1A1 tank. The approach, called "the maturation development process," focuses on improving the maintainability of the critical, high-tech components of a weapon system throughout its lifecycle. The benefits of the approach are the achievement of full designed performance and of savings in support costs.

The research reported here was conducted under a project entitled *An Evolving Action Plan for Implementing Weapon System Management Concepts in Future Army Environments*; however, the research is highly synthetic and also draws upon results from several previous RAND studies. The project was jointly sponsored by the Strategic Logistics Agency, the Army Materiel Command, and the Combined Arms Support Command. The project funding was supplemented by the Strategic Logistics Agency. The project is managed within the Military Logistics Program of the Arroyo Center, directed by Dr. John Halliday.

The research should be of interest throughout the Army logistics and acquisition community.

The Arroyo Center

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Army Regulation 5-21 contains basic policy for the conduct of the Arroyo Center. The Army provides continuing guidance and oversight through the Arroyo Center Policy Committee (ACPC), which is co-chaired by the Vice Chief of Staff and by the Assistant Secretary for Research, Development, and Acquisition. Arroyo Center work is performed under contract MDA903-91-C-0006.

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Summary

Now is a critical time for the Army to understand and address the especially difficult R&M (reliability and maintainability) challenges presented by high-tech components. New weapon systems will increasingly depend on such components in order to achieve the technological "margin of superiority" that U.S. forces have relied upon to overcome quantitatively superior foes. Without effective management of the R&M of these systems, their full designed performance may not be achieved and support costs may greatly exceed projected budgets.

The objective of this research is to develop policies and procedures to help the Army reduce the burden caused by the failures of certain high-tech (chiefly digital), high-cost Class IX components. Taken together, these policies and procedures compose an approach to weapon system design and redesign that we term "maturation development." Maturation development seeks to improve the detection, reporting, isolating, and removing of component faults; it also identifies and implements changes to component design that improve R&M. Maturation development can be applied both to new systems, such as the proposed Comanche helicopter, and to major modifications ("upgrades" of fielded systems, such as the Apache helicopter or M1A1 tank.

The R&M Challenge to Sustaining High-Tech Weapon Systems

High-tech equipment largely comprises digital components—compact, complex, multifunction circuit cards. Such components exhibit R&M problems of a fundamentally different and more difficult character than those exhibited by mechanical equipment. In mechanical equipment, R&M problems are dominated by wear processes and by physical failures. Such problems are usually straightforward to detect and isolate, either visually or with simple test equipment. Repair parts tend to have low unit costs.

In high-tech equipment, by contrast, many "failures" are best characterized as instances of degraded performance that appear intermittently and may be related to operational and environmental conditions. Such faults are often difficult to detect because the conditions under which they occur cannot be replicated at the maintenance facility, and they are often difficult to isolate because of the complex

interrelations of circuit boards. Moreover, complex diagnostic test equipment is needed to assist in the fault detection and isolation, and this equipment itself is also high tech and subject to R&M problems. Replacements tend to be extremely expensive, making large stocks prohibitively expensive. In addition, over time specific components may become "lemons," chronically faulty units that move constantly back and forth between repair echelons and weapon systems, delivering little of their full designed performance while consuming a disproportionate amount of support resources.

These high-tech R&M challenges present the double risk of achieving lower weapon system availability at increased costs. Components that are not faulty may be mistakenly removed from weapon systems, while other removed components may be returned to weapon systems without being properly repaired. Support costs rise because of repeated and unnecessary actions and because of the cost of additional, very expensive spares. At the same time, weapon system availability is overstated because some of the systems that are considered fully mission capable actually contain one or more faulty components.

Maturation Development

Because of the avionics suites in its most advanced aircraft, the Air Force has acquired a great deal of experience with the R&M challenges posed by high-tech components, and RAND has worked with the Air Force for over a decade on acquisition and support strategies for high-tech aviation electronics. These strategies focus on minimizing fault detection and isolation problems and improving the logistics supportability of fielded systems. More recent RAND research for the Army indicates that advanced Army systems such as the Apache and M1A1 tank evidence R&M challenges that are fundamentally the same as those experienced by USAF systems. The Army can benefit from the Air Force's experience and previous research investments.

Based on its research into the high-risk R&M characteristics of high-tech weapon systems, RAND has developed a new incremental process—called "maturation development"—for managing the development and sustainment of R&M over the life cycle of a complex weapon system. The goal of maturation development is the delivery of full designed performance of the weapon system under mission conditions and the rapid restoration of full design performance when malfunctions occur. It provides for early resolution of systemwide R&M problems and the identification of lemon components that make their way to the field. Early identification and resolution of R&M problems can be a highly

effective means of understanding the cost drivers of readiness and sustainment and of managing the support cost of the weapon system. Maturation development can be applied to both new systems and to fielded systems.

For new weapon systems, maturation development begins early in the life cycle during research and development. Continuous data collection on the performance of components--even prototypes--during this period provides the basis for a description of the physics of failure modes that is important for later analysis. These early data are also important input for the estimation of R&M budgets.

Maturation development of new systems intensifies during low-rate production and early fielding. The approach calls for a dedicated period of intense operation, data collection, and analysis immediately upon fielding a weapon system. This period would occur during the latter portion of the engineering and manufacturing development phase, now called the low rate of initial production (LRIP) period. The purpose of this period would be to detect and isolate design deficiencies by intensively operating the components in a fixed configuration within the environment where they will normally operate. Although the maturation development period coincides with operational test and evaluation, it would be primarily development testing conducted (observed) and supported by engineering personnel, followed by a detailed analysis of the data gathered. The output of the maturation data collection period is a set of engineering changes to modify the full-rate production version of the components so that the major R&M problems are resolved.

Maturation development continues into high-rate production and fielding. The database set up in the early acquisition phases and used extensively in the maturation development period would then be used to monitor performance and to identify and isolate lemon components. This continuing effort permits analysis of the effects of configuration changes, of aging, and of new mission requirements or operational environments.

An alternative implementing strategy for maturation development applies to systems that are already fielded--and for which only a limited database exists. These high-tech systems are likely to still exhibit less maturity than one would desire in a high-tech weapon system. Indications of an immature system include a high degree of difficulty in fault detection and fault isolation, along with a set of components that consume large amounts of logistics resources. This strategy calls for the establishment of a limited database to identify the extent of the problem and to isolate the most immature electronic units. A performance-oriented tracking of the equipment repair system would allow the weapon

system manager to identify which components are consuming the most logistics resources and focus his attention on those components.

Information Requirements to Support Maturation Development

A key element of the maturation development process is a well-developed management information system linked to an integrated R&M database to facilitate efficient and effective resolution of the R&M problems associated with high-tech components. The database should be integrated across functions and echelons as well as through time. An integrated system is needed because, as suggested above, R&M effects in a complex weapon system can appear in the system at locations and echelons that are remote from the cause. For example, what appears from the operator's perspective to be a radar problem may in fact be a power supply problem. Because fault indications in these complex systems are not always unambiguous, patterns must be observed and recorded. This complexity requires linkages across the elements of the weapon system and across time. The managemen information system must allow the manager to assess the performance of elements of the weapon system and support system, which requires the ability to link data from operation; fault indication at the end item, including those provided by the built-in-test (BIT), intermediate test, and repair and depot test; and repair over a period of time.

Among the data elements needed to support maturation development are those associated with unit-level and intermediate and depot or contractor maintenance, including data associated with diagnostic test equipment at all levels, with administrative and transportation processes, and with maintainers. For at least some selected component types, individual tracking by serial number will be required to permit the identification and correction of lemons as they emerge.

The maturation development process poses more demanding data requirements than can be met with current data systems. However, it is well within the state of the art to incorporate "smart chips" into the design of high-tech weapon systems to lessen the data collection burden, perhaps to the point that it is even less of a burden than currently exists.

Conclusion

We expect the need for maturation development to increase in the 1990s. The Army already needs to achieve required weapon system availabilities at lower costs. Moreover, the Army can expect to encounter increasing R&M problems as

its inventory of weapon systems, both through upgrades and new procurements, becomes increasingly sophisticated technologically.

In implementing maturation development, the Army faces four kinds of obstacles, each of which can be overcome:

- Cost obstacles: Maturation development requires some increase in development costs. Since these costs must be weighed against savings in support costs over the system's life cycle, it is important to establish the capability to measure support costs accurately. The operational benefits of improved high-tech R&M performance must also be considered.
- Technical obstacles: Maturation development requires the development of new measures of R&M performance and improved data collection and analysis capabilities. Innovations in automated data collection, including the use of "smart chips," may greatly reduce the data collection burden.
- Environmental obstacles: Maturation development can be expected to delay the fielding of a new system or upgrade for a few years. During the Cold War, procurement processes were highly compressed because of competition from the Soviet Union. With today's reduced risk, there should be less resistance to maturing systems before fielding them.
- Organizational obstacles: Maturation development requires a closer integration of engineering and logistics activities and of organic and contractor activities. Incentive systems, including contracts, may need to be changed to reflect an increased emphasis on improving the fault removal efficiency of the maintenance system and the availability of fully mission capable weapon systems while reducing total life cycle costs.

The potential benefits of implementing the maturation development process for managing the R&M of high-tech weapon systems are twofold: first, the achievement of full designed system performance, which contributes to genuine mission capability; and second, reduction in support costs over the life cycle of the system.

Acknowledgments

We are deeply indebted to several RAND colleagues who played important roles in conducting studies whose results and implications are synthesized in this report. Jean Gebman, in particular, has devoted well over 10 years to the study of maturation development in projects sponsored by the U. S. Air Force. Morton Berman's and Marc Robbins' analyses of the reliability and maintainability performance of the M1A1 and the Apache, respectively, strongly influenced us and helped us to develop a case for persuading the Army to adopt maturation development.

Several members of the DoD and Army logistics and acquisition communities contributed reviews of early versions of this document that helped us to improve the rigor and credibility of the argument. These include LTG Leon Salomon, Deputy Chief of Staff for Logistics, who encouraged us to consider Army application of the concept, which was originally developed for the Air Force. Further support was provided by Herbert Fallin, Keith Charles, and LTC James Smith of the Office of the Assistant Secretary of the Army for Research, Development, and Acquisition. Robert Keltz, currently the Principal Deputy for Logistics for Army Materiel Command, provided guidance for this effort when he was Director of the Strategic Logistics Agency. That guidance was further refined by the current Director of the Strategic Logistics Agency, William Neal. Numerous leaders at the Major Subordinate Commands of Army Materiel Command responded to a previous version of the report strengthening its recommendations. Some of these important contributors include Thomas House, Daniel Rubery, and Ernest Young. We want to thank them and their staffs for their support and guidance throughout the development of this concept.

Many of our RAND colleagues have contributed insightful reviews of this document. These include Patricia Boren, John Folkeson, John Halliday, Vincent Mabert, and Marc Robbins. Formal technical reviews were provided by Lionel Galway and Arnold Levine.

We thank Elizabeth Sullivan for her patient and expert efforts in preparing the manuscript for publication. Christina Pitcher provided a timely and careful edit that improved the clarity of the exposition.

Abbreviations and Acronyms

Symbol	Definition
-A	Army-sponsored research
-AF	Air Force-sponsored research
Bad Actor	See Lemon
BIT	Built-in-test (system)
BITE	Built-in-test-equipment
CAMS	Core Automated Maintenance System
Class IX	Reparable weapon system components
CONUS	Continental United States
DoD	Department of Defense
DRIVE	Distribution and repair in variable environments
Dyna-METRIC	Dynamic Multi-Echelon Technique for Recoverable Item Control
ECM	Electronic countermeasure
ECP	Engineering Change Proposal
EETF	Electronic equipment test facility
FMC	Fully mission capable
FRA	Forward repair activity
HUD	Heads-up display
ILS	Integrated logistics support
Lemon	Chronically faulty component
LHX	Light helicopter experimental
LPRF	Low-power radio frequency
LRIP	Low rate of initial production
LRU	Line replaceable unit
LTU	Laser transceiver unit
M	Maintainability
MEP	Mission Equipment Package
MLRS	Multiple Launch Rocket System
MTBF	Mean time between failure
MTBR	Mean time between removal
N-	RAND Note
NEOF	No evidence of failure
NRTS	Not reparable this station
ODS/S	Operation Desert Shield/Operation Desert Storm
R	Reliability
R&D	Research and development
R&M	Reliability and maintainability
R-	RAND Report
RBM	Readiness-based maintenance
REMIS	Reliability and Maintainability Information System
SARDA	Secretary of the Army for Research, Development and Acquisition
SRU	Shop replaceable unit

TADS/PNVS	Target Acquisition and Designation Sight/Pilot Night Vision Sensor
TBO	Time between overhaul
TEU	TADS electronics unit
TICARRS	Tactical Interim CAMS and REMIS Reporting System
TMDE	Test, measurement, and diagnostic equipment
Type A	A fault that is definite and repeatable
Type B	A fault that is intermittent and difficult to isolate
USAF	United States Air Force
WSSM	Weapon System Sustainment Management

1. Introduction

Now is a critical time for the Army to understand and address the especially difficult reliability and maintainability (R&M) challenges presented by high-tech weapon systems. As the Army moves forward in the development of new weapons and the modification of existing ones, it incorporates more high technology in its designs. High-tech items are particularly important in two senses: First, they are critical to achieving the "margin of superiority" that advanced technology provides to U.S. weapon systems; and second, they are extremely expensive to develop, repair, and replace. Through the next decade and into the next century, high-tech weapon systems will greatly dominate the Army force structure. The Army will come to depend on far fewer numbers of these systems because of their lethality and will depend on a much leaner logistics structure, in part because of their presumed reliability and ease of maintenance. The upgrading of existing systems and the development of new weapon systems require an approach that provides the margin of superiority expected, the availability of fully mission capable weapon systems needed, and the ease of maintenance needed in a power projection environment.

Purpose

This report advocates a new approach to enhancing the R&M performance of high-tech weapon system components (i.e., Class IX components). Analyses of the proposed Comanche helicopter suggest that eight high-tech components will cause 70 percent of the downtime.[1] Fielded high-tech weapon systems such as the Apache, M1A1, F-15, and F-16 have similar dominating components with such features.[2] The new approach to managing R&M, which we term "maturation development," has the potential to increase weapon system availability (and hence operational capability) while also reducing total life cycle costs. The approach can be applied both to new weapon system acquisitions and to major modifications (upgrades) of fielded weapon systems.

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[1]For related analyses, see Berman et al. (1989). The estimate reported here does not appear in that report. It was uncovered in later analyses by the project team.

[2]Robbins et al. (1991); Berman et al. (1988); Gebman et al. (1989).

Increased Weapon System Availability

Historically, the current approach to acquisition management has typically achieved a great deal during the preproduction phases of the system life cycle in terms of improving weapon system availability. This has been accomplished through a strong emphasis on improving the reliability of high-tech components. However, the benefits that accrue from this approach are often exhausted by the time of fielding, and the approach has typically not been able to achieve the full designed weapon system availability goals before the system is fielded.

Under maturation development, both reliability and maintainability improvements are sought during the earlier life cycle phases, but during low rate of initial production as maintenance occurs and data become available, the focus shifts more acutely to maintainability improvements before the system is fully fielded. More specifically, maturation development seeks to improve the processes of detecting, reporting, isolating, and removing faults so that the incidence of repeated faults is greatly reduced. It also seeks to identify and implement modifications to component designs that exhibit poor maintainability. The added emphasis on maintainability, we argue, will permit the achievement of full designed weapon system availability and performance goals as well as the continuous improvement of maintainability and weapon system availability rates throughout the life cycle.

In the case of new weapon systems, maturation development has major implications for the period of low rate of initial production, where many changes to the current approach are required to ensure that full designed availability goals are met before high-rate production and fielding and that the support system is positioned to continuously improve weapon system availability during fielding. In addition, this approach has implications for the preproduction phases of the life cycle, where some steps (e.g., data collection and integration) must be taken in preparation for the later focus on improving maintainability.

In the case of major upgrades to fielded weapon systems, maturation development has major implications for modification implementation. As with new weapon systems, during the period preceding full-rate production and retrofitting there are significant changes to the acquisition strategy. Because many of the upgrades will include changes to the high-tech electronic suites, the strategy should include planning for a maturation of the design of these components and the use of test beds to fully understand the capabilities and effects of the proposed design.

Reduced Total Life-Cycle Costs

Maturation development is also expected to reduce total life-cycle costs under most circumstances. For example, when this approach is applied to a new weapon system or major upgrade, more costs will accrue before full production, because of the increased activity focused on improving maintainability; however, during the fielded life of the new or modified system, costs would be much lower, reflecting the maintainability improvements. Fewer maintenance actions mean fewer test stands and, most important, fewer maintainers.

When maturation development is applied to a fielded system, there is less potential for cost savings over the remaining life cycle. Careful case-by-case analysis would be required to determine whether the benefits of maturation development, both in terms of cost and performance gains, outweigh the costs. In the Service's limited experience in applying elements of the maturation approach, there have been instances in which some changes (redesign of specific components) to improve R&M performance were identified but judged too expensive to implement. This judgment was based primarily on consideration of the size of the fleet that required retrofitting.

It is important to note that the expected cost savings would not be fully captured using the current data collection systems. Our research indicates that a large portion of the maintenance costs associated with high-tech components are due to actions taken in response to degraded system performance, such as multiple removals and tests in search of an elusive fault, actions that are not currently captured for diagnostic use.

Should Weapon Systems Need to Be Matured?

An obvious objection to the maturation development process is that it should not be necessary if a weapon system is designed and built properly in the first place. Therefore, according to this argument, improvements should be sought in those activities first.

This objection is based on an incomplete understanding of the complex nature of the performance degradations in high-tech weapon system components. It is important to recognize that the highest quality engineering and manufacturing cannot obviate the need for a maturation period after the research and development phases.[3] As is demonstrated in Section 2, a simple cause and effect

[3]There are a number of analogues to maturation development in commercial industries. One is the practice of software firms in distributing "beta" versions of new products to a limited set of users.

relationship between removals of components and a hard failure does not exist in the complex interdependency of an integrated electronic system; rather, anomalies in hardware, software, and environment, and the effects of operational missions interact to produce performance degradations. This complexity--and the complexity of the built-in-test (BIT) system--results currently in removal processes that are frequently not linked to the underlying physical causes of the lack of performance in the weapon system. Further, these degradations are frequently not reproducible in the relatively quiescent maintenance environment. The diagnostic equipment used at higher echelons of maintenance do not simulate the mission environment. Moreover, the usual assumption is that higher-level tests are complete and there is no need to verify that the malfunctions identified by the higher-level test are indeed the same problems that resulted in the removals. This assumption creates the potential for significant removal problems to go undetected in the maintenance tests.

Maturation development relies strongly on a period of intensive field operation, data collection, and analysis. Without a detailed field data collection and engineering evaluation resulting in appropriate hardware and software modifications, experience shows that performance degradations are certain to be present in complex weapon systems. These anomalies lead to poor reliability, maintainability, and availability, generating high support costs while reducing operational capability. Unless they are removed, they will persist for the life of the weapon system.

Organization of This Report

The remainder of this report describes the maturation development process, drawing upon research of both Air Force and Army weapon systems. Section 2 demonstrates (1) that high-tech components have failure characteristics that differ fundamentally from those of mechanical components, affecting operational performance and complicating diagnosis and repair, and (2) that traditional approaches to managing R&M, which were developed for mechanical systems, are not well suited to high-tech components. Section 3 describes maturation development and explains how its approach to managing high-tech R&M would differ from what is currently done at each life-cycle stage. Special attention is

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These users test the new product in what could be described as its "normal, operational environment" and uncover bugs and design deficiencies that the firm can choose to correct before distributing the full-market version. Another analogue is the use of pilot plants in the processing industries. Rather than build a full-scale factory employing a new process, a firm builds a small but fully functional plant to test the new concept operationally. What these practices have in common is the recognition that complex mechanisms cannot be fully matured until information is available regarding how they perform while operating normally in a genuine environment.

devoted to the discussion of the period of low-rate production, because this is where the differences are most pronounced. Section 4 explains the kinds of data that are required to support the new approach, arguing the need for an R&M data system that is integrated across echelons and functions and over time. Section 5 offers concluding observations and suggests directions for implementing the maturation development approach in the Army.

Appendix A sets the maturation development approach in the context of a comprehensive concept of logistics management under development at RAND: Weapon System Sustainment Management (WSSM).

2. The R&M Challenge to Sustaining High-Tech Weapon Systems

R&M Problems Characteristic of Mechanical Equipment

R&M problems faced by the Army reflect the technological sophistication of weapon systems. An army consisting solely of mechanical equipment has simple R&M problems dominated by wear processes and easily diagnosed physical failures. Mechanical equipment is characterized by faults that exhibit symptoms that are observable in all operations of the faulty piece of equipment, whether in actual field use or in test. These can be referred to as "Type A" faults. The effect of the fault is usually seen close to the location of the failed part, and the cause and effect relationship is traceable either visually or using fairly simple test equipment. Repair parts for mechanical equipment tend to have low unit costs. Moreover, when managing the R&M performance of mechanical equipment, the problems in different functional areas--such as testing, repair, and supply--do not usually interact closely. Rather, a problem can typically be identified cleanly as a problem in a specific functional area at a specific echelon.

R&M Problems in High-Tech Systems

The latest generation of weapon systems relies on high technology--complex, integrated, electronic subsystems--to enhance mission performance and provide combat multiplier effects. High-tech components require sophisticated built-in test equipment (BITE) and test, measurement, and diagnostic equipment (TMDE) to help detect and isolate faults for repair. Nevertheless, the prevailing assumption, derived from experience with Type A faults, is that only one failure occurs at a time and that tests are complete and accurate. Driven by this assumption, the maintenance of high-tech systems is supposed to proceed in the following fashion (the current process is represented schematically in Figure 2.1).

Components fail in operation and the failure is detected, either by some BITE or by the operator. The fault is then reported by the operator to a maintenance technician. The maintenance technician then diagnoses the fault using some combination of skill, technical data, and TMDE. He will then either repair the

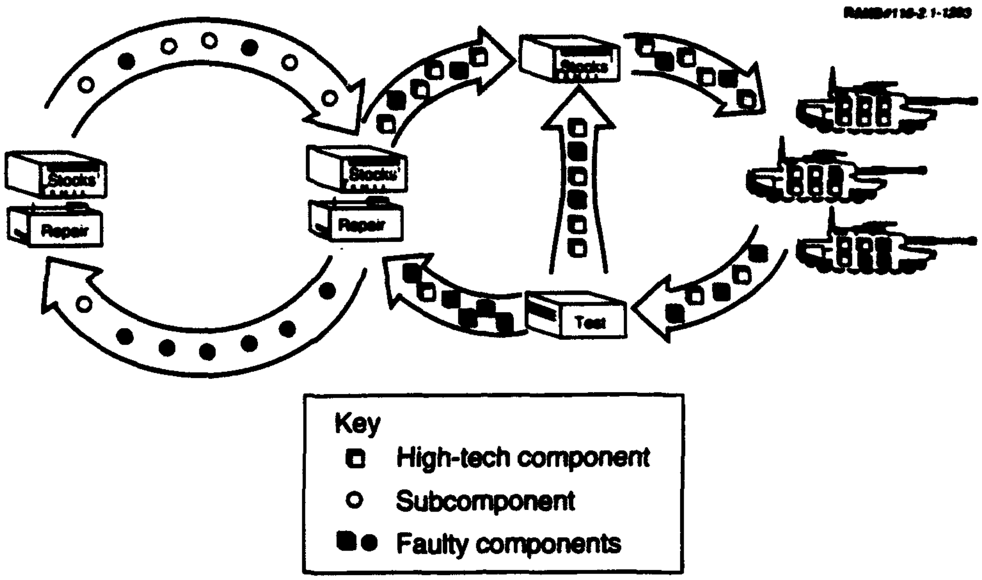

Figure 2.1—Schematic Representation of the Maintenance System for High-Tech Components

faulty component or replace it with a "good" one and send the faulty one to the next higher echelon for repair.

At this stage, the faulty component (a line replaceable unit, or LRU) will also be subjected to additional fault diagnosis by a maintenance technician using some combination of skill, technical data, and TMDE. He will then either repair the faulty LRU by repairing a subcomponent or replacing the subcomponent with a "good" one and sending the faulty subcomponent to the next echelon for repair. The "good" LRU is then made available for subsequent use in repair of a weapon system. The faulty subcomponent, called a shop replaceable unit (SRU), is sent for repair by a maintenance technician who will diagnose the fault using some combination of skill, technical data, and fault detection and isolation equipment. He will identify a faulty part and replace it with a "good" part.

Ideally, every detected fault will be reported, and every reported fault will be repaired following expedient fault diagnosis. Unfortunately, that is not the case with the maintenance of high-tech components. The fault removal process of high-tech components runs into difficulties in all three phases—fault detection, fault reporting, and fault isolation and repair. As a result, the current system is flooded with both false negatives—components that are thought to be broken but are not—and false positives—components that are thought to be fixed or "good" but are not.

These difficulties arise because high-tech equipment is characterized by what can be termed "Type B" faults: complex, mission and environmentally dependent faults that do not have stationary observability. These present serious challenges to providing sustained weapon system availability and to controlling support costs. These intermittent faults are not systematically recorded or measured by traditional R&M testing because the detection systems are not designed to capture their occurrence. As a result, some high-tech weapon systems considered to be fully mission capable (FMC) may in fact contain components exhibiting intermittent faults. Weapon system availability within a unit may be overstated and may not be sufficient to meet a commander's operational objectives.[4]

LRUs in high-tech electronic subsystems typically have many SRUs, most of which are multifunction circuit cards. These circuit cards are a complex integration of subcomponents with a high degree of engineering sophistication that makes possible the state-of-the-art performance. Usually each of these circuit cards is designed to be diagnosed and replaced at the shop, if necessary. The complexity of these high-tech SRUs leads to a diagnostic problem where the existence of a problem is frequently disguised and the cause of a malfunction is not apparent.

Moreover, the range of failure modes in high-tech components is very large, especially as encountered in the field, and includes degradation modes that are difficult to observe under quiescent conditions. BITE, in particular, has limited coverage of the performance specifications and limited capability to observe performance in the mission environment.

The complexity of the BITE and TMDE causes an additional set of R&M problems: The high-tech components of the test equipment itself fail frequently and cannot be repaired easily. They can be very expensive: For example, an electronic equipment test facility (EETF) that tests 78 different types of LRUs costs $10 million. TMDE has many possible faulty components, and most test stands remain not mission capable for long periods. Because so few test stands are available, bottlenecks occur that cause many weapon system LRUs to be placed on "awaiting maintenance" status or sent to a depot for repair.[5]

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[4]High-tech LRUs tend to be very costly ($20,000 to $200,000 each), which makes large stock buys prohibitively expensive as an alternative to expeditious repair.

[5]An analysis of the benefits of consolidating test equipment at higher echelons is presented in Berman et al. (1988).

In sum, high-tech equipment exhibits R&M problems of a fundamentally different nature than those displayed by mechanical equipment.[6] Rather than simply "breaking," as mechanical components do, high-tech equipment more typically fails in the sense that it intermittently exhibits degraded or aberrant performance. These intermittent faults result in problems in fault detection, reporting, and isolation. The following subsections describe each of these problem areas in turn.

Fault Detection

Fault detection occurs when either the BIT detects an anomaly and the operator observes the BIT, or when the operator observes the anomaly directly. Several factors contribute to the detection problem (including some of the same factors that contribute to reporting problems).

General Degradation vs. Failure. High-tech systems experience "graceful" degradation by design, but the degree of degradation is often difficult to measure. In fact, some elements of the system may be operating correctly, while other elements of the system may have degraded operation but remain undetected by the BIT because of varying degrees of degradation.

Limited Opportunities. Restricted use of certain subsystems--especially during peacetime operations--limits the opportunities of the BIT to detect faults. Different radars, for example, are rarely tested over the full range of design performance during peacetime.

Intermittently Observable Symptoms. Because many high-tech components are sensitive to dynamic environmental conditions, faults present in one operational environment may not appear in less hostile environments, such as those found in shops or in benign field tests. Some symptoms may be triggered by vibration or temperature occurring in operation and cannot be duplicated easily at a repair facility.

Incomplete and Imperfect BIT System. The BIT was developed to alleviate some of the fault detection problems. It is, however, limited to detecting only what it was designed to detect. Sometimes, it does not detect a fault because it was not designed to test for that fault. At other times, it reports a fault that does not exist because the BIT itself is faulty. Many of the BIT systems are not comprehensive, many of them are not continuous, many do not indicate multiple

[6]Gebman (1989).

faults, and most do not indicate the severity of the fault. Finally, because some of the faults are intermittent, the BIT can appear to be irregular.

Fault Reporting

Unless a fault is reported, weapon systems are considered FMC. Inaccurate fault reporting causes a skewed and potentially dangerous view of weapon system availability because weapon systems with no reported faults are assumed to be ready for their mission. Operators are the principal source for reporting faults to maintenance. When operators observe anomalies and do not report them, no maintenance occurs. When operators do report an anomaly, but maintainers are unable to confirm it, the suspected component is considered to be good. Frequently, the record of the unconfirmed anomaly is unavailable for future use by maintainers.

A request for maintenance is influenced by many considerations, among them the following.

Mission Requirements. The operator might choose not to initiate a repair request for a system not required for the next mission, such as a night vision system for a daytime mission. He also may delay a repair request if he lacks confidence in the ability of the maintenance technicians to repair the system, for example.

General Degradation vs. Failure. High-tech systems rarely fail catastrophically, but still fail—where failure means the inability to provide the full designed capability. Generally, these systems fall victim to faults that degrade their performance. More often than not, operators must make a judgment about a symptom of a fault (i.e., degraded or inconsistent performance) and determine whether it is serious enough to be a reportable discrepancy. Though "graceful" degradation is generally a design criterion, the degree of actual degradation is often difficult to judge.

Limited Opportunities. Restricted use of certain subsystems during peacetime limits the operator's experience in determining a fault. Target acquisition and fire control radars, for example, are rarely tested over the full range of design performance during peacetime.

Operator Workload. The operator may be unable to record (even verbally) the environmental conditions that triggered the fault indication because it occurred at a time when there were other demands for his attention. It is easy to

understand why an operator may be unable to provide all the information needed by a maintenance technician.

Fault Isolation

After a fault is detected and reported in a high-tech weapon system, it may be difficult to isolate it to a particular component or set of components. Frequently the cause of the malfunction is ambiguous. A complex electronics fault may manifest itself in any number of components that are linked, making isolation to the malfunctioning LRU or SRU difficult. Furthermore, because electronics are sensitive to environmental conditions such as temperature and vibration, the evidence of their failure may be transient. The ability to isolate the malfunctioning components may be very difficult in the relatively quiescent environment of a maintenance shop.

The result of difficult fault isolation is an increased number of false removals (i.e., no evidence of failures [NEOFs]). Moreover, technicians in search of a fault may remove and test a series--or "chain"--of several related LRUs. The more "related" one LRU is to another in the weapon system, the more likely it is that their removals will be positively correlated.[7] False removals and chains are especially undesirable because they *increase* support costs without a concomitant increase in weapon system availability.

"Lemons"

High-tech systems have also revealed a new R&M phenomenon, the emergence of "lemon" LRUs. A "lemon" is an individual LRU that exhibits chronic performance degradations that are not common to other components of the same design. Lemons circulate repeatedly through the maintenance system, creating an enormous burden (through repeated removal and attempted repair) while contributing very little to operational capability. Evidence from RAND studies conducted for the Air Force (discussed in more detail below) shows that specific lemons can consume 20 times the number of SRUs as do well-behaved LRUs and provide only a fraction (3 percent) of the service time. These LRUs are not necessarily born bad but appear to become faulty over time for reasons that are not yet well understood.

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[7]Robbins (1991).

Examples of High-Tech R&M Problems

The four R&M problems appear to be endemic to high-tech systems: That is, they are not characteristic of the systems of only one Service or another. On the one hand, this means that the Army cannot hope wholly to avoid these problems; on the other hand, it means that the Army may be able to benefit from the experience of the other Services and apply some of their lessons learned.

For well over a decade, the Air Force and RAND have worked together to acquire a great deal of knowledge about the R&M characteristics of high-tech avionics. The bulk of the research focused on approaches to minimize fault detection and fault isolation problems and to improve logistics supportability of fielded systems.[8] More recent RAND analyses of advanced Army systems, such as the M1A1 tank and the Apache helicopter, evidence R&M challenges that are fundamentally the same as those experienced by Air Force systems in the mid- to late-1980s.[9] It may be that the Army can benefit from the Air Force's experience and previous research investments.

The next section presents real-world evidence of the four R&M problems drawn from the aforementioned RAND studies. We point out that none of the examples should be considered unique to the weapon system. Rather, we wish to show that these problems are endemic to high-tech equipment and therefore typify the R&M performance of a variety of high-tech weapon systems. The examples below will be drawn from studies of the Air Force F-16A/B aircraft and F-15C/D aircraft and the Army AH-64 helicopter and M1A1 tank.

Experience with Fault Detection and Reporting

A study that RAND conducted for the Air Force in 1984 as part of the F-15/F-16 Radar R&M Improvement Program uncovered an interesting set of phenomena.[10] Operators did not always report a symptom of a fault to maintenance; and when they did, the field technicians were not always able to duplicate the fault and diagnose a problem. The BIT might have detected a fault during operation, but field technicians were unable to duplicate symptoms of the fault and consequently made no repair. Field technicians may have removed an LRU and sent it to the shop, but the shop technicians could find no evidence of

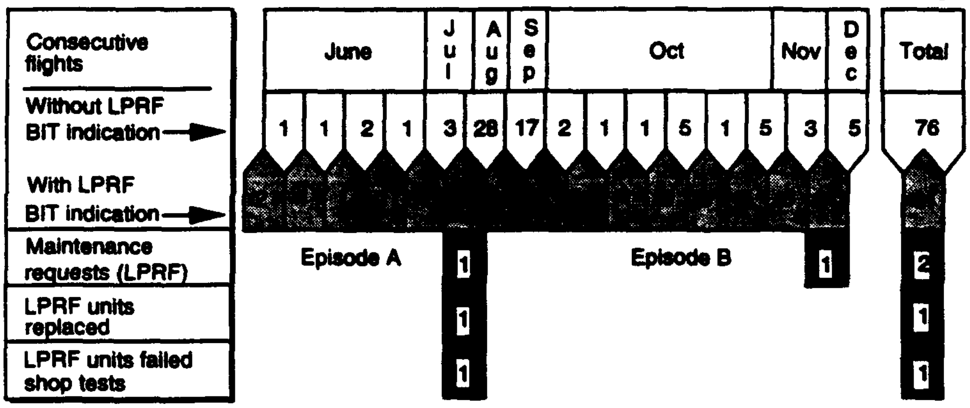
[8] A good survey of the work done in this area for the past 25 years is provided in unpublished research by Gebman et al., on lessons for future avionics from research with the Air Force.

[9] The M1A1 study is documented in Berman (1988). The AH-64 study is presented in Robbins (1991).

[10] See Gebman (1989).

failure (thus, the LRU was considered an NEOF). Similarly, shop technicians may have removed an SRU from an LRU and sent it to the depot, but the depot technicians found that the SRU retested okay. Many items had some maintenance performed on them, consuming lots of logistics resources, but few repairs were made.

Faults Are Not Reported. Figure 2.2 shows the events surrounding one F-16A/B's low-power radio frequency (LPRF) unit in the radar system. Throughout the six-month study period there was an irregular pattern of BIT indications for the LPRF--the first two flights detected something, the third flight did not, the next four flights again did, the next flight did not, etc. This pattern suggests a reason for the reluctance of the operator to file a report and illustrates the inherent limitations of the BIT.[11] Overall, the BIT indicated 41 faulty flights but the pilot reported only two to maintenance. The first fault report was made in July after 12 previously ignored BIT indications; the fault had deteriorated to the point where a circuit board in the LPRF started generating smoke that entered the cockpit. After the LPRF was replaced, there were 28 consecutive fault-free flights. Eventually the BIT detected 29 additional faults before the operator reported the second problem to maintenance in December. The bad LPRF was not removed and remained installed on the aircraft at the end of the



SOURCE: F-16 A/B Radar Maturational Development Data and Analysis Phase 1984–1985.

Figure 2.2—Example of Fault Reporting/Detecting Problems (F-16A/B)

[11]However, the BIT system for the F-16 generates few false positive indications. That is, when it detects a fault, one usually exists, even if the BIT does not detect it on every flight.

period.[12] It is important to note that the aircraft at this point was still considered FMC throughout most of the period by standard reporting systems despite repeated evidence that it contained a faulty component. While this one example of the fault reporting problem is more extreme than the typical case, the bottom line is that for every five indications of a fault, whether detected by the BIT or the operator, only one was reported to maintenance for repair.

Maintenance Technicians Need History of Fault Indications. While it might be assumed that the LPRF was performing up to standard on the 76 flights that were fault-free from the BIT's perspective, a review of the pilot's observations provides a different picture. As Table 2.1 shows, at times the operator noted degraded performance that was not picked up by the BIT. After the new LPRF was installed in July (Episode A), the operator reported a problem to maintenance on only two occasions, one of which had not been BIT detected.

It appears that fixing the LPRF problem was inadequate in part because the maintenance technicians were deprived of the history of the BIT-detected faults and operator observations. Table 2.1 shows that the lack of this information precluded the proper corrective actions. The column labeled FMC indicates

Table 2.1

Weapon System Operators Do Not Always Request Maintenance Actions When They Observe Faults
(data from radar in F-16A aircraft no. 0752 gathered during F-16 A/B Radar Maturation Development Data and Analysis Phase 1984-1985)

Date	Problem Observed	BIT Indication?	FMC?
July 17	Lock-on problem	–	Yes
July 19	Smoke in cockpit	Yes	–
July 23	Lock-on problem	Yes	Yes
July 26	Lock-on problem	–	Yes
July 26	Degraded performance	–	Yes
Aug 10	Lock-on problem	–	Yes
Aug 13	False targets	Yes	Yes
Sept 10	False targets	–	Yes
Sept 11	False targets	–	Yes
Oct 15	False targets	Yes	Yes
Oct 16	False targets	Yes	Yes
Oct 26	False targets	–	–
Nov 26	Degraded performance	Yes	–
Jan 10	Degraded performance	–	Yes

[12] At the contractor's request, the LPRF was eventually removed from the aircraft in January 1985 and tested by the contractor.

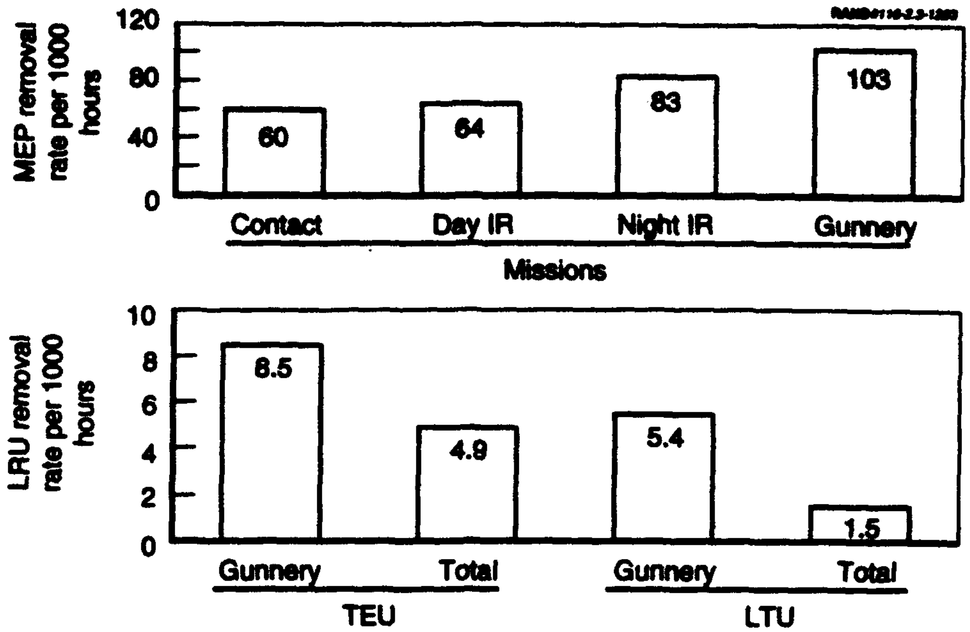
whether the operator reported the weapon system to be FMC. On October 26, the operator reported a need for maintenance because of numerous false targets even though the BIT did not detect a fault. The maintenance technicians, unaware of the BIT history, conducted BIT ground tests that also showed no evidence of failure. The technicians took no further action and instead waited to see if the operator asked for maintenance again, which he did after numerous flights with BIT indications (not shown). Again, they executed the BIT on the ground and found no indication of a fault. They again chose to take no further action.

We speculate that if the maintenance technicians had seen the history of fault indications, it is unlikely they would have allowed the LPRF to remain in the weapon system as long as they did. Thus, their performance was not an instance of poor maintenance, nor can the operator be blamed for poor fault reporting. Rather, this series of episodes illustrates the inadequacies of the established R&M approach to meet the challenges presented by high-tech failure modes. The established approach relies on (1) a data system that collected indications of a fault when an operator believes it is severe enough to call for maintenance and (2) maintenance procedures that suggest a system is fully mission capable if its faults cannot be duplicated in a ground test environment. The standard data collection system is simply not comprehensive and integrated enough to detect the faults that were occurring and to aid in the isolation of the problem. The analysis presented here relied upon the research team's special data collection effort.

Fault Reporting Increases When Operators Face Combat. Table 2.1 provides evidence that operators may frequently report a weapon system to be FMC for an imminent mission even though they have noted faults and degraded performance. Moreover, as Figure 2.3 suggests, even in training, operators increase their rate of fault reporting when faced with a combat-related mission, reflecting their increased concern with the mission capability of their weapon systems. The figure reports removals of the Apache helicopter Mission Equipment Package (MEP), the Target Acquisition and Designation Sight (TADS) electronics unit (TEU), and the laser transceiver unit (LTU).

Ongoing RAND studies of the Army's and Air Force's experiences in Operation Desert Shield/Storm provide additional, though preliminary, evidence that fault reporting rates increase when weapon system operators are faced with combat missions.[13] It appears that the number of faults (i.e., repair requests) reported for

[13]Gebman et al., unpublished RAND research on finding and fixing bad actor avionics.



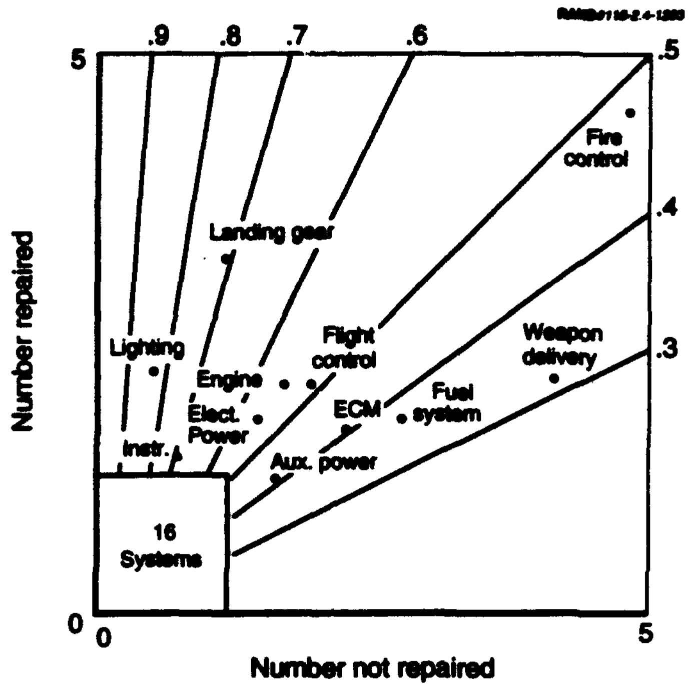
SOURCE: RAND data collection at Ft. Rucker, 1989.

Figure 2.3—Apache High-Tech Component Removal Rates for Combat-Related Missions Exceed Those for Other Training Mission Types

Air Force and Army high-tech components were more than twice the peacetime values. When given a choice as to whether a system is mission capable or not, the operators made a very different choice when faced with combat. Thus, what appears as a maintainability problem is, in fact, a mission reliability problem.

Experience with Fault Isolation

Maintenance Technicians See No Evidence of Failure. Figure 2.4 illustrates the problem with fault isolation by depicting the fault isolation efficiency associated with 27 types of subsystems on the F-16A/B aircraft. The steeper the slope of the line associated with a specific weapon system, the higher the fault isolation efficiency. For every 100 flights, 16 subsystems had one or no repair actions. The fire control system averaged nine requests for repair: Half were repaired and half were not because maintenance could not isolate the problem (either the BIT could not duplicate the malfunction, or the technicians could not duplicate what the operator saw). In other words, the efficiency of fault isolation at the flight line was about 50 percent.



SOURCE: F-16 A/B maintenance data collection, 1985.

Figure 2.4—Flight-Line Fault Isolation Efficiency (F-16 A/B) per 100 Flights

Figure 2.4 also illustrates how much easier it is to isolate faults in mechanical equipment compared with high-tech equipment. Note that lighting and landing gear, both mechanical components, have fault isolation efficiencies near 80 percent on the flight line.

This research also tracked fault isolation efficiency beyond the flight line (not shown in Figure 2.4).[14] For the radar (flight control), 51 percent of the reported faults were repaired on the flight line. The intermediate shop fixed 68 percent of the radars it saw, and the depot repaired 80 percent of the radar SRUs it saw. On the surface, some of these efficiencies might appear acceptable, but a closer examination indicates that the overall fault isolation efficiency for the radar is just 28 percent: In other words, about one in four requests for maintenance resulted in a repair action.[15]

[14]The research was based on a special data collection effort involving 16,000 flights of the F-16 in 1984-1985.

[15]The overall efficiency rate of .28 is derived from multiplying the efficiencies at each of the three levels: .51 x .68 x .80.

Good LRUs Are Removed to Isolate the Bad. Difficult fault isolation creates an additional maintenance burden because technicians may mistakenly replace good LRUs. Table 2.2 shows one aircraft's avionics LRU replacements for a three-month period. Note that on September 15, maintenance technicians replaced the four radar system LRUs and the electronics unit of the heads-up display (HUD) in response to a reported fault. The transmitter continued to be a problem and was replaced four more times. All told, the transmitter was replaced five times, ten times more than the expected replacement rate of 0.5. (And the transmitter still may not have been the culprit.)

The Army has experienced similar fault isolation problems with the M1A1 tank and the AH-64 Apache helicopter. RAND analysis of Army data uncovered that the M1A1's fire control system was experiencing chains (removals of multiple boxes to isolate a fault in one) in 27 percent of its removals, with an average chain length of three LRUs.[16] The early fielding of the Apache fleet suffered to a great degree from the same maintainability problems as other high-tech weapon systems. Poor fault detection was evidenced by a 40 percent error rate in BIT-detected faults. Poor fault isolation resulted in high NEOF rates: 25-30 percent for its MEP LRUs, and 29 percent for those in the TADS/Pilot Night Vision Sensor (PNVS). Some high-driver LRUs had NEOF rates as high as 50 percent at

Table 2.2

Inadequate Diagnostics Create Problems in Sustaining Mission-Effective Avionics (removals of avionics LRUs from F-16 A/B no. 0021)

Date\ LRU	Flight Control Panel	Electronic Computer Assembly	Air Data Computer	Low-Power Radio Frequency Unit	Trans-mitter	Digital Signal Processor	Com-puter	Electronics Unit
Sept 3		1st						
Sept 4		2nd						
Sept 15				1st	1st	1st	1st	1st
Sept 22					2nd			
Sept 26			1st					
Oct 1					3rd			
Oct 8				2nd				
Oct 10	1st							
Oct 26				3rd				
Oct 27					4th	2nd		
Nov 26					5th			
Total	1	2	1	3	5	2	1	1
Expected	0.1	0.2	0.2	0.5	0.5	0.3	0.3	0.3

[16]The study is reported in Berman (1988), though this particular finding remained unpublished.

Fort Rucker, the Army Aviation Center and School. These NEOFs resulted from fault isolation problems at the flight line.[17]

Effects of Poor Fault Isolation. These examples demonstrate the potential for adverse effects on the logistics structure. Supposedly good LRU spares provided to field maintenance and good SRUs provided to intermediate-level maintenance are still potentially faulty. Further, the handling of each component uses valuable supply, maintenance, and transportation resources.

What does poor fault isolation mean for weapon system effectiveness? Many faults remain in the system unfixed. Weapon systems might be repaired with a defective LRU that had malfunctioned yet showed no evidence of failure to the maintenance technician. Similarly, faulty LRUs might be "fixed" with defective SRUs. Overall, the result is an overstatement of available weapon systems that can deliver their full designed performance.

Fault Removal Efficiency

By combining these three elements of the maintenance process (fault reporting, detection, and isolation), we emerge with a view of the seriousness of the maintainability problem. The F-16 study found that only 20 percent of the faults were reported and that of those only 28 percent were repaired. This means that fault removal efficiency[18] is a mere 5 percent–i.e., only 1 in 20 faults are repaired by maintenance.

Low fault removal efficiency is not a problem peculiar to the F-16A/B radar. A parallel collection of engineering data for the F-15C/D radar offers another example.[19] In this case, the BIT system indicated faults in one of every three flights. When the BIT detected a fault, it correctly isolated the fault only one-third of the time and misdiagnosed the other two-thirds (either no fault existed or the BIT identified the wrong LRU as the faulty component). It also failed to detect faults that actually existed in another one-third of the flights. As a result,

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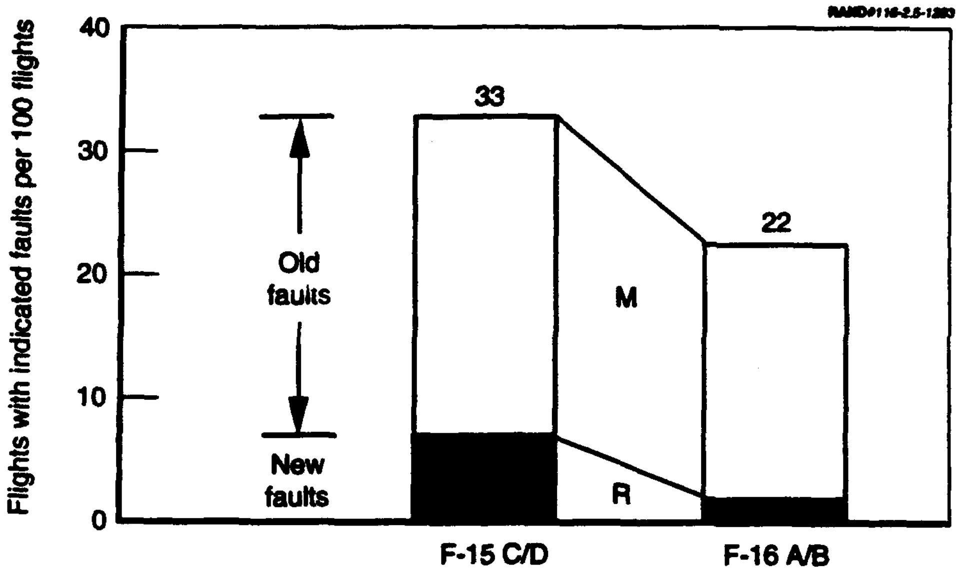
[17]It is our understanding that a large effort on the part of the Army led to a marked improvement in this aspect of the Apache's performance. The Army established the Apache Action Team in the early fielding stage to improve the reliability and maintainability of the helicopter. However, improvements were implemented after the bulk of the fielding and concentrated on mechanical parts.

[18]Fault removal efficiency is a measure of total maintenance system performance. It is defined as the percentage of faults at the end item removed by replacement of faulty components. In a multiechelon maintenance system, the performance of each echelon contributes to the system's fault removal efficiency.

[19]Additionally, a set of special studies was done on the electronic countermeasure (ECM) systems for the F-15 C/D and the F-16 A/B and similar results were found. These studies are reported in Gebman et al., unpublished RAND research on reliability, maintainability, and maintenance of electronic countermeasures for tactical air warfare.

the BIT system was not believed. Faults remained in the system for a number of flights before repair was made. For 20 percent of the LRUs sent to the intermediate shop for repair, the shop implemented repair actions that were unrelated to the faults that occurred in flight. Moreover, 85 percent of the faults identified had been identified previously.

Figure 2.5 shows the seriousness of the maintainability problems for the F-15 and F-16 radars. The figure shows that of all indicated faults, relatively few are new faults; most are old faults that have been previously detected but not removed.[20] The persistence of old faults implies that the R&M challenge of high-tech systems is predominantly a problem with maintainability rather than reliability. Old faults greatly increase the burden on the logistics structure and greatly reduce the availability of FMC weapon systems.



NOTE: F-15C/D Radar and F-16A/B Radar Maturational Development Data and Analysis Phase 1984–1985.

Figure 2.5—Old Faults (i.e., Maintainability Problems) Dominate New Faults (Reliability Problems) (F-15C/D radar and F-16A/B radar)

[20]Some faults are "removed" through a maintenance action--such as resetting a button--other than removal of a suspected faulty component.

Experience with Lemons

A small subset of high-tech subsystems exhibit the lemon problem: Particular LRUs show failure and degraded performance rates that are starkly higher than those seen in other items of identical design.[21] Although some evidence suggests that the incidence of lemons rises with the electronic complexity of the LRU's design, one study found that approximately 9 percent of any given high-tech LRU type--for example, the transmitter in a radar--exhibit this behavior.[22] Their differing failure modes may be triggered by particular characteristics of the environment and may not be present in test bench environments. Because these problems do not occur in the normal maintenance test environment, they can cause repeated removals without (attempted) repair removing the cause of the problem.

An Air Force study done in 1985 and 1986 on the F-15C/D radar unit provides an example of the lemon problem. Table 2.3 shows the number of individual radars that made a large number of trips to the intermediate repair shop. During the three-month exercise, programmable signal processor #1059 visited the shop 12 times, and transmitter #0067 visited the shop 10 times. These observations led to a special data collection at Bitburg in 1984 to more fully define the problem.

As expected, some specific units were removed more frequently than others. Figure 2.6 shows the radar digital processors that were removed and replaced four or more times during the year. On average across the fleet, this type of LRU was removed 1.9 times during the year and 0.6 times per 100 flying hours. Particularly noteworthy are the five digital processors that had to be replaced more than 15 times per 100 flying hours. These five are considered candidate lemons and subject to further analysis.

The implications on the field maintenance activity are obvious. Technicians had to take many repair actions that provided very little value in terms of weapon system availability. These lemon LRUs amounted to about 9 percent of the processors but provided only 3 percent of the flying hours.

The implications for the entire logistics structure are even greater. Table 2.4 shows that the lemons had a mean time between removal of four hours and accounted for one-third of the intermediate shop returns. Even worse, they

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[21]The problem of lemons among weapon systems and weapon system components was first investigated by RAND in the early 1960s (W. H. McGlothlin and T. S. Donaldson, 1964, and T.S. Donaldson and A.F. Sweetland, 1966). Some other RAND research often refers to lemons as "bad actors."

[22]Gebman et al., unpublished RAND research on finding and fixing bad actor avionics.

Table 2.3

Some Specific Components Make Many Trips to the Shop

Number of Visits per Unit	Number of Units	Unit Type and Serial Number
12	1	Programmable signal processor #1059
10	1	Transmitter #0067
9	1	Programmable signal processor #1015
		Transmitter #0525
8	4	Receiver #0471
		Analog signal processor #0564
		Programmable signal processor #1057
7	1	Antenna #0855
6	7	Various units
5	17	Various units

NOTE: F-15 radar units at Bitburg, 1984.

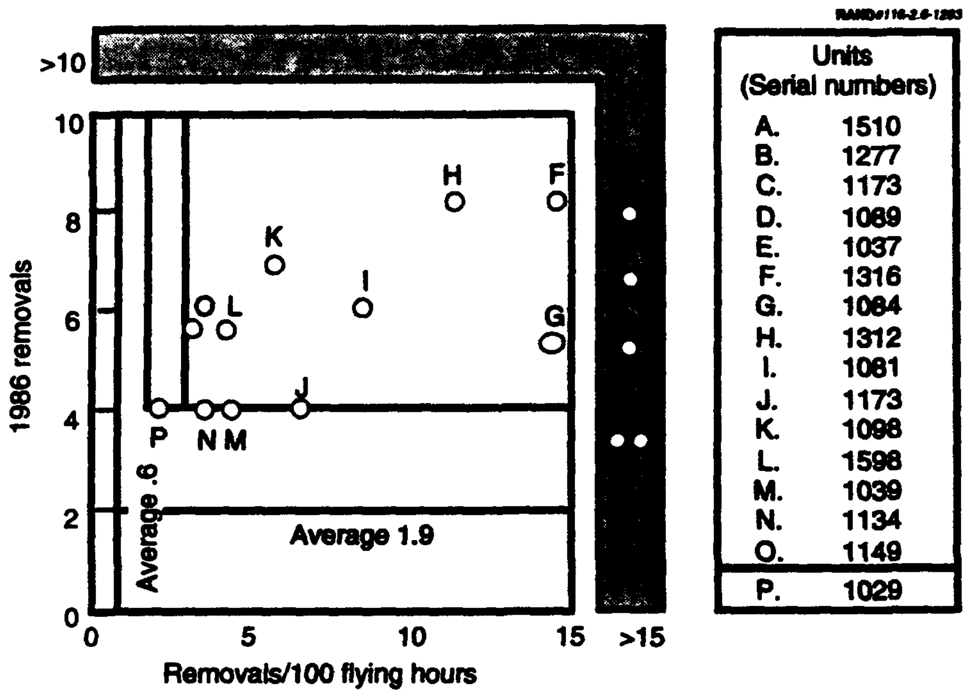

Figure 2.6—Lemon Digital Processors Were Replaced More than 15 Times per 100 Flying Hours

Table 2.4

Radar Lemons Consumed 20 Times More SRUs than Did Other LRUs

	Good LRUs	Lemon LRUs	All LRUs
Total visits	768	382	1150
Mean time between removal (MTBR) (hours)	34	4	24
NEOF rate	40%	35%	39%
Reseat and adjust	24%	24%	24%
Remove and replace	33%	34%	33%
LRU not reparable this station (NRTS)	1.7%	0.5%	1.3%
SRUs consumed	362	181	543
SRUs consumed per 1000 flying hours	2.1	44.0	3.1

consumed 20 times the SRUs consumed by good LRUs for every 1000 flying hours. That amounts to a 50 percent increase in the number of SRUs sent to the depot for repair.

The implications of lemons for weapon system effectiveness are also serious. The lemon problem does not appear to be limited to only one LRU for a given weapon system, or even for a given high-tech subsystem. Each type of high-tech LRU appears, from our studies, to be subject to lemon units; all eight high-tech LRUs in the F-15 radar have lemons.[23] In an F-16 fleet, if lemon LRUs are randomly distributed among the weapon systems, there is a 55 percent probability that any given weapon has at least one lemon LRU in it.

Although little is known about their causes, our observations of the Air Force experiences indicate that these LRUs are not manufactured as lemons but become sick over time. Detailed engineering analyses of a number of the isolated LRUs found that these units suffered problems under environmental stresses, i.e., thermal or vibration, that were not detectable on benign test benches.

While we have used examples of USAF systems to describe the lemon problem and its ramifications, we do not mean to imply that only Air Force systems are susceptible. Rather, we have had a greater opportunity to study this problem in Air Force systems, and the Air Force has generally made greater use of complex

[23]Other high-tech systems, like the ECM systems, in both the F-15 and F-16 appear to have similar lemon units.

high-tech components.[24] As yet, Army weapon systems have not incorporated the level of complexity that is more commonplace in the Air Force, but that is highly likely to change over time. Thus, we would predict that current Army systems do not generally suffer from a lemon problem to the same degree. However, Figure 2.7 shows signs of just such a problem emerging, and it is likely to grow far greater as the Army uses more high-tech components and their complexity increases. The figure shows the distribution of lemons across LRUs of one of the more sophisticated Army subsystems, the Apache TADS/PNVS. In the TADS/PNVS, one LRU, the TEU, is by a large margin the most complex piece of electronics along the dimensions noted above. And, unsurprisingly in view of the Air Force experience, that LRU shows strong signs of lemon-like behavior. Yet even the TEU is simple technology compared with what the Army intends to buy in the future.[25]

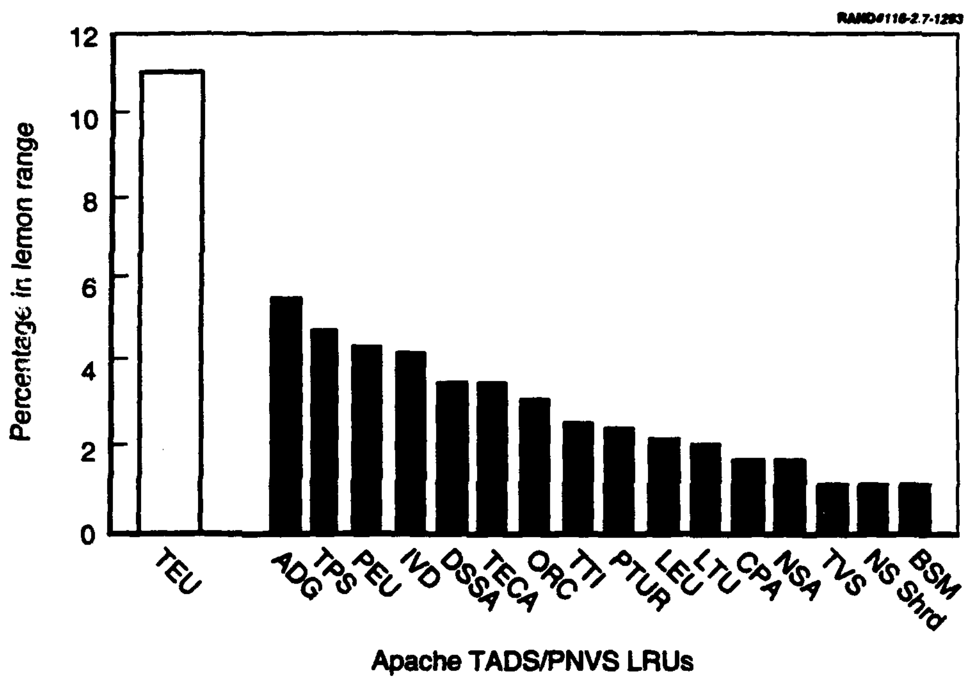

Figure 2.7—Lemons May Be Emerging in Army Weapon Systems

[24]High-tech electronics are becoming increasingly complex, measured along three dimensions: the number of circuit cards in a box, the density of the circuits on the cards, and the interconnections between the cards (and to other components).

[25]Our RAND colleague Marc Robbins provided us with this example of lemon behavior in an Army weapon system.

Basic fault reporting, detection, and isolation deficiencies further complicate the lemon problems. We noted earlier how the deficiencies in the automatic fault detection and fault isolation procedures have led to a lack of confidence in these systems by operators, which have led them to ignore some of the indications of faults. We also noted how the lack of total reporting of all indications of malfunctions have led to difficulty in fault isolation. This results in as many as one-half of the units being returned to the system as serviceable with no repair made. Additionally, because lemon LRUs exist, some of the "repairs" that are made have no relationship to the cause of the problem. Our data indicate that as many as 20 percent of the repairs that are made--i.e., remove and replace an SRU--"fix" components that are not broken.

Operational Effects of R&M Problems

R&M problems that are not properly detected, reported, isolated, and removed not only create a burden on the maintenance system; they also have deleterious and potentially dangerous effects on operational planning and capability. If weapon system availability rates are overstated by the present data collection and analysis methods, then planning factors for weapon system availability are probably incorrect and planning factors for weapon system support requirements are probably underestimated.

There is also evidence that weapon system operators become aware of the limitations of the maintenance system to remove faults and adjust their own behavior accordingly. Many fault indications are not reported by operators apparently because they are aware of the difficulty that maintainers face in isolating and removing faults. This leaves the unfortunate situation in which components exhibiting indicated faults remain in weapon systems.[26] Of course, operators may change their behavior depending on the mission they are about to conduct. While fault indications are frequently ignored in peacetime, they are not ignored in war. Even during exercises that required great precision, operators report more faults than during normal peacetime training operations.[27] Preliminary analysis of data about Operation Desert Storm indicates that demand rates for some components in some cases were twice the peacetime rates. Even in peacetime, demand rates vary by mission type. As Figure 2.4

[26]This is especially so with the F-16 radar for which RAND, through a special study, found that the BIT system is reliable when it indicates a fault. In at least 95 percent of the cases, when the BIT detected a fault, a fault existed. But pilots did not reliably request maintenance.

[27]Studies of Coronet Warrior and ECM test programs revealed a higher demand rate than normal peacetime rates.

showed, removals of Apache MEP LRUs increase in more demanding, combat-type missions.

Summary and Implications

The characteristics of high-tech weapon systems indicate a need for a new approach to R&M management. Because new weapons and major upgrades use more high-tech components, the problem will only get worse. The research already done in this area shows that:

1. New weapon systems, or major upgrades with high-tech subsystems, will have R&M problems when they are fielded.
2. Although there is always room for improvement in logistics reliability, there appears to be greater room for improvement in the design of the maintainability of the new weapon systems.
3. The maintainability characteristics are complex because some "failures" are difficult to detect and the ability to repair these failures is elusive.
4. These maintainability improvements will require design changes, which should be incorporated into the design as soon as possible.
5. Detection and isolation of design deficiencies must generally rely on a significant amount of information from systems in an operational environment for analysis. This information is best obtained during the initial, low-rate production phase for two reasons: first, because that is the first time that information on a production model in operation is available; and second, because corrections to deficiencies found can be implemented in models produced during full-rate production, avoiding the possibly prohibitive expense of retrofitting the entire line.
6. Even after correcting the design deficiencies, a number of individual lemons will exist that need to be identified and managed separately.

The first four elements are primarily observations that need to be conveyed to managers; the last two elements call for the development of a new methodology. Section 3 of this report describes such a methodology: the "maturation development process."

3. The Maturation Development Process

Faced with the R&M challenges posed by fielded high-tech weapon systems, the Services have developed various innovative, albeit ad hoc, ways to cope with them.[28] Our focus here is on advocating a systematic, research-supported approach to reduce the problems for existing weapon systems and for high-tech weapon systems now being developed or modified.

As noted in the examples cited in Section 2, many of the maintainability problems uncovered in previous RAND research were identified through an intensive data collection and analysis effort. Those analyses identified major fault reporting, fault detection, and fault isolation problems, as well as the existence of the lemon problem. The success of these analyses suggests a maturation approach that involves using special data collection and analysis efforts--different in kind and degree from what programs typically have done--to enable weapon system sustainment managers to identify the need for specific engineering changes and improve both sustainment and weapon system capability.

However, each of the examples of Service experience illustrates applications of only selected elements of the maturation development process and only to fielded systems. None exemplifies application of the full process to a new weapon system. The purpose of this section is to provide a detailed description of the full maturation development process as applied to a new weapon system. The section argues the need for such a process, outlines its phases over the course of a system's life cycle, and explains how the adoption of such an approach would alter or augment the activities currently undertaken in each stage of the weapon system's development and fielded life.

[28]During Operations Desert Shield/Storm, Army support for the Apache was innovative. The level of intermediate support--in terms of TMDE--was 160 percent of doctrinal levels. Depot-level support was provided in the Continental United States (CONUS) and also in theater in the form of special repair activities (later called forward repair activities--FRAs) and contractor support, as well as in CONUS. The rapid transportation system that was developed both intertheater ("Desert Express") and intratheater ("Camel Flights") helped to further improve the availability of these weapon systems. These adaptations reflect both the ability to respond to unusual situations and the need to treat high-tech systems differently. Studies need to be conducted to determine the exact effectiveness of these adaptations. See Robbins and McIver, unpublished RAND research.

Need for a Maturation Development Process

The high-risk R&M characteristics of high-tech systems require a new incremental process for managing the development and sustainment of R&M over the life cycle of a complex weapon system. Maturation development is a continuing process to deal effectively with the anomalies in the R&M performance of the weapon system.

Objectives of Maturation Development

The goal of maturation development is the delivery of full design performance of the weapon system under mission conditions and the rapid restoration of full design performance when deficiencies exist. Maturation development provides for early resolution of systemwide R&M problems and identification of lemon LRUs that make their way to the field. Early identification and resolution of R&M problems can be a highly effective means of controlling the cost drivers of readiness and sustainment and of managing the support cost of the weapon system.

The potential benefits of implementing such a concept are twofold: first, the achievement of full designed system performance, which contributes to genuine mission capability; and second, the reduction in support costs over the life cycle of the system. Setting performance considerations aside, these cost savings are more than sufficient to offset the costs of implementing the maturation development process if undertaken early enough to avoid a major retrofit of an entire production line.

Overview of the Process

Maturation development calls for continuous data collection and analysis on the R&M performance of a weapon system. For new weapon systems, data collection begins in the phases preceding fielding and intensifies during the period of initial fielding. Maturation development could also be applied to fielded systems, with modifications. In such a case, the period of intense data collection and analysis would be implemented in conjunction with a system upgrade.

The purpose of the period of intense data collection and analysis would be to detect and isolate design deficiencies by intensively operating the components in the environment within which they will normally operate. The period of maturation development coincides with what is now known as the period of

initial operational test and evaluation. It would involve primarily development testing with direct participation by contractor engineering personnel, followed by a detailed analysis of the data gathered. During this period the Army would be "measuring operational experience, organizing and recording R&M-related data, interpreting the data, and drawing conclusions about the root causes of the dominant R&M problems that are responsible for any shortfalls in needed R&M characteristics."[29] The output of this dedicated phase feeds the engineering process to facilitate changes to the full-rate production versions of the high-tech components so that the major R&M problems are resolved.

These activities of intensive weapon system operation, data collection, analysis, and subsequent engineering improvements must be preplanned and incorporated into the acquisition process. While the planning must occur throughout the entire acquisition process, the bulk of the operation and data analysis activities would occur during the latter portion of the engineering and manufacturing development phase, i.e., the low rate of initial production (LRIP) period. LRIP is defined by law to be that period preceding the full-rate production during which (1) the production base is established, and (2) operational test and evaluation of the weapon system is conducted to verify the operational effectiveness and suitability of the system.

The database capabilities set up in the early acquisition phases and used extensively during LRIP would then be used in a much more modest fashion during production and fielding in order to analyze performance and to identify and isolate lemon LRUs.

A necessarily more limited version of the maturation development concept could be adopted for systems that are already fielded and for which only a limited database exists. These systems are likely to still suffer the lack of maturity one would desire in a high-tech weapon system. Indications of an immature system include a high degree of difficulty in fault detection and fault isolation, along with a set of LRUs that consume large amounts of logistics resources. This approach would call for the establishment of a limited database to identify the extent of the problem and to isolate the most immature electronic units. A performance-oriented system for the tracking of equipment repair would allow the weapon system manager to identify which LRUs are consuming the most logistics resources and focus attention on those LRUs.

[29]Gebman et al. (1989), p. 72.

The stages of maturation development are discussed in detail below. For this discussion, data sufficiency is assumed throughout; a detailed discussion of data requirements to support maturation development is reserved for Section 4.

Maturation Development Through the Life Cycle

This subsection describes how maturation development would be implemented at each phase of a weapon system's life cycle, from concept exploration to operation and support. In each phase, we focus on the engineering and logistics activities because the maturation development concept calls for these to become more integrated.[30] Then we describe briefly the additions to each phase that are needed to implement a maturation development program. Table 3.1 summarizes these descriptions.

Concept Exploration and Definition Phase

Purpose. In this, the initial weapon system development phase conceptual studies are used to develop alternative solutions for design, production, logistics, and testing during the development of the weapon system. The only hardware are breadboards and prototypes, typically focused on new technology components.

Current Engineering and Logistics Activities. The chief engineering activities are requirements analyses, functional analyses, trade-off studies, preliminary allocations, preliminary design synthesis, and analytic evaluation leading to alternative system concepts. Preliminary functional allocations and error budgets for subsystems are generated and configuration management baselines are established.

The chief logistics activities in this period are (1) the investigation of alternative support concepts to develop an integrated logistics support (ILS) strategy and (2) the adoption of these concepts into the engineering system design to influence the resulting product definition. Initial planning for the structure and scope of the logistics program (in the form of ILS) occurs in this period. Currently the focus of ILS is on the strategy and support concepts for hard failures and their impact on the support system.

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[30]A number of other very important activities (e.g., contracting) also occur during each phase that, for brevity's sake, we do not discuss here. Clearly these other activities are also affected by the decisions made in logistics and engineering.

Table 3.1

Acquisition Process with Maturation Development

Approximate Time (Yrs)	Program Phase	Purpose of Phase	Engineering/ILS Activities	Focus of Activities
0	Concept Exploration and Definition Phase	Conceptual studies Alternative solutions • Design • Production • Logistics • Test Breadboards and prototypes	Configure management baselines Develop ILS strategy Influence product definition Conduct open architecture studies of system, BIT, and integrated data	ILS strategy and support for hard failures Planning for evolution of weapon system
2	Demonstration and Validation Phase	Identify and analyze major alternatives Conduct competitive demonstrations Identify technical and economic risk Develop prototypes	Conduct functional configuration analysis Identify/define/assess logistics implications of alternatives Select major alternative Collect prototype diagnostic and anomaly data Conduct initial planning of maturation data collection	Conduct system support design Plan for support development using maturational data collection Begin assembling integrated data using R&D component prototype data
5	Engineering and Manufacturing Phase, Part 1	Design and test selected alternatives Design trade-offs Test system Design engineering prototype Design production prototype	Detail design/synthesis/prototype Design the logistic support system Ensure ILS is integral part of design trades Test elements of the support system Collect prototype diagnostic and anomaly data in integrated database Develop maintenance budget for system Plan maturation data collection and analyses	Detailed design of support Detailed plan for intensive data collection and analyses

Table 3.1—continued

Approximate Time (Yrs)	Program Phase	Purpose of Phase	Engineering/ILS Activities	Focus of Activities
8	Engineering and Manufacturing Phase, Part 2 (Low Rate, initial production)	Initial production model Verification of production process	Collect and analyze production diagnostic data Freeze design Field initial unit Conduct intensive data collection and analysis	Verify reliability Conduct maturation data analyses to ensure maintainable diagnostics and support
	Maturation data collection		Develop modifications for significant support problems Analyze cost and support performance	
	Develop modification		Define implications of intensive data collection	
11	Verify maturation modification		Conduct verification of modifications	
	Production and Deployment Phase	Full rate production	Acquire production support items Collect and analyze factory test data for maintenance effects	Verify design Continue evolution of support

Table 3.1—continued

Approximate Time (Yrs)	Program Phase	Purpose of Phase	Engineering/ILS Activities	Focus of Activities
14	Operation and Support Phase	Deployment	Deliver system and all requisite items of support concurrently Correct mission deficiency **Verify full fielded diagnostic and maintenance system performance**	Track reliability **Track and respond to maintainability problems and opportunities**
17		User modifications Production improvements	**Track lemons** **Improve maintenance process** **Analyze support implications and opportunities of performance ECPs** Support cost studies Support post production Design modifications for product improvement	

NOTE: Activities added under maturation development are shown in bold.

Focus of Activities Under Maturation Development. Under maturation development, the purpose of this phase does not change. However, there is a shift of focus in the engineering and logistics activities.

For example, during the engineering studies for alternative functional solutions, more attention would be given to studies of the costs and benefits of using open architectures that would ease system modification later in the life cycle. Open architectures should also be considered in the development of preliminary BIT concepts. Open BIT architectures facilitate the later modification of sensing and testing elements.

Another important added activity under the maturation development concept during this phase is explicit planning for integrated data collection and analysis of system malfunctions, anomalies, and performance. The maturation development concept includes and depends strongly on integrated data and information systems. A well-developed management information system linked to an integrated R&M database is needed to facilitate efficient and effective resolution of R&M problems. This phase must include the preliminary planning for an integrated database to support such analysis, including the capture of the prototype phenomena for use in later analysis of hardware behavior.[31]

The management information system must be integrated because, as noted earlier, in a complex weapon system, R&M effects can appear in the system at locations and echelons that are remote from the cause. For example, what appears to be a radar problem may in fact be caused by an inertial navigation system that is providing erroneous velocity information to the radar. Because fault indications in these complex systems are not always unambiguous, patterns must be observed and recorded. This complexity requires data linkages across the elements (hardware, software, and test equipment) of the weapon system and across time. These management information systems must allow managers to assess and evaluate across the weapon and the support system, which, in turn, requires the ability to link data from 1) operations; 2) fault indication at the end item, including BIT; 3) intermediate test and repair; and 4) depot test and repair over a period of time.

In this initial period of weapon system acquisition, much work is done on critical components such as special integrated circuits or sensor elements. At this stage, the first R&M data become available in the form of failure data on the prototype components. Failure mode analyses in later phases can benefit from the data

[31] The next section addresses the capabilities and contents of the integrated database in more detail. It also compares these requirements with those of current databases.

collected and analyzed in this early phase. The data from engineering tests can be used to start a description of the physics of failure modes that is important for later analysis. This process can begin even though equipment exists only in breadboard form and software exists only in pre-prototype form.

Demonstration and Validation Phase

Purpose. The purpose of this phase is to identify and analyze the major system alternative configurations and to identify technical and economic risks. Demonstrations are conducted to decide between alternative designs for those areas of risk using developmental prototypes of portions of equipments and subsystems. The hardware available during this phase consists of advanced development prototypes.

Current Engineering and Logistics Activities. The chief engineering activities are the refinement of the studies done in the first phase and the extension of the design to configuration synthesis and engineering development models. As test and evaluation of significant portions of equipment are conducted, data gathered are used in selecting lower risk alternatives and further refining the analyses.

The chief logistics activities are the identification, definition, and assessment of logistic implications of the major system alternatives to influence the selection of the major system alternative. This selection includes an identification of projected resources needed to support the system. Among these resources are the types of test equipment, types of spares, types and skills of maintenance technicians, and quantities of each. The focus of the ILS in this period is on the design of the initial support system.

Focus of Activities Under Maturation Development. Under maturation development, there would be two major additions to the engineering and logistics activities: (1) the capture of anomaly data from prototype testing in an integrated database and (2) planning for further refining the logistics support system using maturation data collection during LRIP (described below).

The first of these additional activities is important because anomalies that occur in testing frequently seem to be only curiosities at their first occurrence. If such data are captured in an integrated database that is used later for analysis of anomalies in operation and test of the system, they can contribute to understanding the modes that degrade performance (as opposed to hard reliability failures).

The second additional activity is important because the intensive data collection and analysis that takes place during LRIP requires planning to ensure that the time and resources that will be needed are acquired. As noted earlier, maturation development relies on an analysis of detailed data collected during extensive operation of the weapon system in an operational environment. Time and resources to conduct the extensive operation of the weapon system and analyze the data must be planned for. The planning will construct a test program that will allow capture of detailed data on anomalies as they appear. Because the specific anomalies cannot be predicted in advance, the test plans must be general enough to allow for adaptive testing as the anomalies appear. Such adaptive testing is usually possible only when there is not a detailed series of tests that must be passed in order to proceed with the program.

Engineering and Manufacturing Phase, Part 1 (Prior to LRIP)[32]

Purpose. The purpose of this initial period of the Engineering and Manufacturing Phase is to identify and analyze the major alternatives for the weapon system, the included equipment, and final choices in the logistics support structure. It is the first time that detailed "budgets" for R&M are estimated and substantial quantities of R&M data become available. (An R&M "budget" is the detailed allocation of the required R&M performance levels across the hardware, software, and diagnostic test equipment that compose the weapon system; in short, a budget is an estimate of R&M performance.) The focus is on the design and test of selected alternatives. Design trade-offs are made. System tests are conducted using engineering prototypes at first and, later, production prototypes.

Current Engineering and Logistics Activities. Engineering activities include the detailed design, synthesis, and prototyping of the weapon system. Prototype test results are used to refine the design.

Logistics activities include actions to make ILS an integral part of the design trade-offs and to complete the design of the support system. Support items are designed and elements of the support system are tested. The implementation of ILS requires the development of a detailed maintenance support concept and detailed estimates of the R&M of the hardware. Maintenance system design entails the partitioning of the weapon system into subsystems, equipments, and LRUs at the end item. It also defines the test and diagnostic structure covering

[32]"Engineering and manufacturing" is a current DoD term for the phase previously referred to as full-scale development.

BIT, diagnostic procedures, intermediate-level test equipment (if applicable), and depot-level (and/or production) test equipment.

Focus of Activities Under Maturation Development. Under the maturation development concept, three additional activities occur in this initial period of the Engineering and Manufacturing Phase.

The first activity collects data during the operation of the prototype, including information about diagnostic and anomaly events. The data must be collected to allow analysis of a sequence of activities over time. (See Section 4 for a discussion of the analysis of sequenced events.) Because it facilitates analysis of the evolving design, these data must be incorporated into a database that is integrated across functions, echelons, and time.

The second activity uses that data to update R&M budgets. Some of this updating can be tentative in the sense of evaluating what the implications would be if a given anomaly in the factory engineering test appeared more frequently than expected. Such R&M budget impacts are both resources and "flags" for the evaluation of events in the intensive data collection period. Such budgets are critical for the determination of required resources and the control of the program to attain the required R&M performance. The current R&M resource estimation process frequently does not provide for continuing updates during the life cycle of the weapon system and does not provide linkages to other data and information generated in nonlogistics areas of the program. The availability and use of an integrated R&M data system would allow for both updating and linking. Estimates would be derived from the integrated R&M data system and could be used to evaluate and prioritize the R&M issues that arise during development.

The third activity updates and refines the plan for the intensive operation and data collection and analysis that will occur during LRIP. Planning in this phase will consist of five activities.

1. Update the more general planning based on the detailed information available from production prototypes and the methods available for capturing information in the operational maintenance and support setting.
2. Plan for the detailed capture of operational anomalies over all of the echelons of operation and support, including the relation of write-ups, BIT indications, field maintenance procedure indications, and in-factory or in-depot repair test indications.
3. Plan for adaptive testing if detailed engineering data are required for a particular anomaly, subsystem, equipment, or module.

4. Plan the analytical effort to identify significant problems and to evaluate and prioritize fixes.
5. Plan for the development and testing of modifications (design changes to the weapon system) for the significant problems.

Engineering and Manufacturing Phase, Part 2 (LRIP)

Purpose. As currently conceived, the purpose of this phase is to verify the production process for the initial production model and determine the operational effectiveness and suitability of the weapon system.

Current Engineering and Logistics Activities. The engineering and logistics activities of the Engineering and Manufacturing Phase described above continue during LRIP, making use of the larger base of data from the low-rate production testing.

Engineering activity centers on production start-up. This involves verifying the planned production test sequence, dealing with problems in the production processes, and solving problems in the production testing. Engineering is then involved in the production and production testing of the support equipment (including any end item and any intermediate-level test equipment).

Logistics personnel are involved in constructing and testing the support system and updating R&M performance estimates. Production hardware becomes available to test tools, TMDE, documentation, and procedures.

Both engineering and logistics personnel have roles in updating the test and evaluation master plan in preparation for the operational test and evaluation that occurs in the LRIP phase.

Focus of Activities Under Maturation Development. This phase of maturation development concentrates on identifying and correcting support problems. Because reasonable quantities of production models are available in a field environment, extensive identification, analysis, and evaluation of support problems and potential corrections are possible.

Under the maturation development concept, the LRIP phase adds important activities that contribute to the development of a mature production model:

- Intensive operation of the weapon system in the field environment, and the collection and analysis of detailed R&M and operational data, including the

analysis and prioritization of mission effectiveness and life-cycle cost impacts.

- Design and implementation of modifications to the system as judged to be cost-effective.
- Verification of desired effects of the modifications on the system's R&M performance and costs.

From the perspective of maturation development, the goal of the intensive operation of the weapon system and data capture and analysis is not to pass a test requirement, but to understand the proximate cause of all anomalies and malfunctions observed in the field environment.

Intensive Operation of the Weapon System, Data Collection, and Analysis. Under maturation development, the key activity during LRIP is an intensive period of operation during which data on the R&M and operational performance of fielded systems are collected and analyzed. During this period, the configuration of the hardware and software must be frozen to maintain a known baseline for evaluation. The length of this period is a function of the field activity rates: generally speaking, the greater the activity, the more data generated, and thus the shorter the period. The data collection occurs at each level of maintenance in order to permit a comprehensive evaluation of the system's R&M performance and characteristics. The detailed data collection permits engineering analyses of the problems, frequently based on linking the indications from each echelon and from previous indications of anomalies captured in the earlier acquisition phases. (See Table 4.1 in the next section for specific data elements that should be collected during this period.)

During the Engineering and Manufacturing Phase, a significant quantity of detailed information becomes available from engineering tests and from component production tests; this information can be used for detailed failure mode analysis. Test information needs to be captured in the same way that the research-phase information on failure modes was captured. Similarly it must be linked to the engineering knowledge of failure modes and estimates of the frequency of their occurrence. The data from factory testing of components allow the analysis of phenomena that occur in the factory. The results of diagnostic testing from the end item to factory testing of removed components need to be related and tracked over time. This tracking involves resolving the results at different test echelons with engineering tests, including tests of BIT, manual diagnostic procedures, factory test equipment and procedures, and component test equipment and procedures.

The structure and mechanisms to capture and link this information need to be developed and exercised early in LRIP in order to ensure that at each test level--from initial indication of a problem in the end item through repair of SRUs in the factory--the test results can be related. This process ensures that the indications and repair actions at each echelon relate to the same problem. This same information and logic will later be needed in the field to track particular problems and their solutions.

Because of the need for highly detailed, high-quality data, some elements of this data should be collected by an expert team that includes contractor engineers and technicians. Detailed data include a verbal description of the anomalous faulty behavior of the equipment and a description of the complete operational and technical context of the event. The team can ask questions such as the following: "When in the operation did the fault occur?" "Was the fault repeatable?" "Does it occur only in certain situations?" "Was there a BIT indication of the fault?" The team will also be able to ask more specific questions based on the fault history of the particular hardware: "Did you see X faulty behavior under Y conditions?" The team may also be able to suggest specific data collection activities if certain equipment behavior is observed: e.g., "if X fault occurs, please record a certain computer memory location value."

Maturation development requires the capture of data that might not normally be reported by an operator. Frequently during operation, an anomaly may occur that does not result in a registered fault (i.e., the BIT does not recognize the anomaly as a fault or the operator's assessment of the impact of the anomaly for the next mission is that maintenance is not required) but is still an anomaly and needs to be reported. Because the system designers did not plan for this type of anomaly, the BIT may not capture the fault. A system as simple as a tape recorder or nonvolatile computer memory that automatically captures the anomaly, even if only at a major system level, should record the environmental and operational conditions immediately preceding, during, and following the anomaly. In the event such a system fails to capture these events, a debrief of the operator should also occur that includes indications of irregular performance that would not normally lead to a write-up or any request for maintenance. These data are needed to enable evaluation of patterns of anomalies that occur without individually appearing important to the operator or requiring immediate actions. Such a pattern, if it recurs or if it leads to an unacceptable anomalous event, can be critical in understanding the physical and environmental phenomena that caused the faulty performance. The analyzed data can then be used to develop and evaluate solutions for the actual field R&M problems.

The participation of engineering personnel in this phase permits the rapid extension of planned testing to determine particular anomaly mechanisms, operational interactions, and environmental sensitivity as anomalies appear in operation. As opposed to "proof" testing where all of the test points need to be defined before execution, intensive maturation testing is adaptive in order to permit the capture and definition of significant operational anomalies and degradations in system operation and support as they emerge.

Development of System Modifications. Beginning during the intensive data collection and immediately following it is the period for developing and prioritizing modifications for the significant problems discovered during the data collection. These will be implemented through service/deficiency reporting and Engineering Change Proposals (ECPs). The implementation of fixes is a straightforward process when the underlying problem is well understood. Even so, it is critical to test the fix because the degree of improvement can be uncertain and it is always possible to introduce a new problem unintentionally.

Verification of Effects of Modifications. The period of developing modifications must be followed by another similar but less intensive operation, data collection, and analysis period after the fixes determined from the first period's analysis have been made. The second phase is used to evaluate the fixes and assess their overall impact. The history of the impact of substantial changes on weapon system support requirements is checkered with problems. Predicting the success of a group of changes based on engineering estimates of the reduction in support requirements is not an adequate means of establishing a firm base for proceeding with the fleetwide changes in production (or upgrade).

Production and Deployment Phase

Purpose. During the production phase, full-rate production and fielding of a highly capable weapon system occur. Hardware performance is verified to meet specifications. Program management responsibilities transfer from the acquisition to the support communities. Full-rate production equipment is provided to field units with support and support equipment.

Current Engineering and Logistics Activities. Engineering and logistics identify deficiencies and work to correct them. ILS acquires all necessary support items. For the first time, numbers of items undergo the production testing process. With this experience, problems with items not passing tests or passing an initial item test only to fail in a higher assembly test will appear. Early in the production process, the test may be incorrect, the production process may be

incorrect, or the item may require redesign. All of these situations will require engineering changes to correct.

As production progresses, more modifications occur in response to unacceptable yield rates of processes and unacceptable failure rates in higher assembly testing. As support equipment becomes available, its testing may generate changes to deal with support equipment production tests and interface problems.

Focus of Activities Under Maturation Development. After the intensive operation, data collection, and analysis period and subsequent modifications, the data system is used to monitor delivered R&M performance, detect any problems as they arise, and evaluate the impact of configuration changes as they occur. The challenge to configuration control in this period is to document both the changes and the testing of the changes. Because the effects of engineering changes can interact, this is a difficult task.

As the system moves into high-rate production, production test data and operational data become available for a much larger population of items. Before this phase, most of the program effort focuses on design problems where all items of a particular type exhibit the same characteristics. With the larger population, the data system can begin to track such problems as lemon LRUs and SRUs. Identifiable by serial number, lemons exhibit failure modes that are not the same as those exhibited by other items of identical design. Their failure modes may be triggered by particular characteristics of the environment and may not be present in the test bench environment, occurring only in the field environment. Because these problems do not occur in the normal diagnostic test environment, they can cause repeated removals without the associated test and "repair" removing the cause of the problem. This is one reason why it is so important to link the reason for an LRU or SRU removal to the result of the test of that item in repair. Current field experience has shown that the replacement of some "out of spec" component in maintenance is not equivalent to diagnosing and removing the problem that led to the removal of the component from the end item.

Dealing with these problems requires tracking the performance of individual serial-numbered items through their operational use. The collection of all data associated with operational malfunctions, diagnostic test results at each level, and repair actions over time allow identification of lemon components. These data can be compared with the data from the overall population and patterns can be established. When specific serial numbers are identified with anomalous patterns, special diagnostic tests based on the particular environmental and operational circumstances associated with the anomalies can be devised to

identify the particular failure mode involved. After identification of the failure mode, alternatives can be evaluated. If alternatives that involve tailoring diagnostic or repair procedures do not appear cost-effective, the component can simply be removed from service.

Operation and Support Phase

Purpose. This phase overlaps with the previous phase of production and deployment because systems operate and require support as soon as they are deployed. In this phase, the operational command assumes property accountability. Operator-supported product improvements and modifications begin and continue through this period, their number and magnitude depending on the success of production, continuing mission analysis, technological advances, and the achievement of supportability goals.

Current Engineering and Logistics Activities. Engineering personnel and logisticians monitor the delivered performance and develop the user supported changes. The formal reliability monitoring at the wholesale level begins with fleetwide failure data. Engineering supports the development of user-initiated functional upgrades and the reliability work in such areas as fatigue studies and refining the requirements on time-change-out components. Maintainability is primarily addressed through reports from the field regarding deficiencies in manuals and procedures.

Focus of Activities Under Maturation Development. In addition to monitoring and identifying lemon LRUs, this phase of maturation is used to continuously monitor the R&M performance as configuration changes are made. Frequently, engineering changes made for functional improvement or safety concerns result in unexpected R&M problems. Modifications also offer the possibility of incorporating R&M changes that would not be cost-effective to incorporate separately. There is also a continuing need to monitor and evaluate the maintenance and support system as the fleet grows. Some problems that will be important with large numbers of equipment or appear as a consequence of aging do not occur early in the life of a weapon system. Thus, the data system is needed throughout the life of the weapon system, even after production is finished and the system is in full operation. Some special data collection and analysis efforts may be needed through the course of the system's fielding; however, as a rule it is not necessary to continue data collection and analysis at the level of intensity applied during LRIP.

Summary

The maturation development concept starts with the recognition of the extraordinary technical complexity of new, high-tech weapon systems and the understanding that when such systems are newly fielded they will not immediately deliver their full designed performance. It goes on from there to acknowledge that high-tech electronics need to mature, and that maturation can be managed by weapon system sustainment managers throughout the life cycle of the weapon system. This contrasts with the traditional view of mechanical systems that R&M characteristics are an output of the initial design phase and that once design is over the job is basically done. This recognition of the special character of high-tech components requires planning for an intense maturation period early in the fielding of a new weapon system and planning for an integrated R&M data system to support maturation of the R&M characteristics of the weapon system over the life of the system. The benefits of such an effort are both improved weapon system availability and savings in total life cycle costs.

The concept also recognizes the need for system assessment and evaluation of causes rather than of effects only. In a complex weapon system (including the support system), R&M effects can appear in the system at locations and echelons that are remote from the cause. Indications may be ambiguous in isolation, so patterns must be observed and analyzed. To assess R&M performance of the weapon system accurately requires the ability to link data from operations and from all echelons of repair over a period of time. Dealing with this complexity requires linkages across the elements (hardware, software, and test equipment) of the weapon system and across time that have not been requirements of traditional R&M data systems.

The main difference in approach between this new concept and the way high-tech R&M is currently managed involves the analysis of data to reveal patterns that indicate anomalies and their causes. To do that, it is essential that the weapon system sustainment manager track sequences of indications and actions over time rather than only counting events at an echelon (removals at the weapon system, for example). An intensive maturation development period immediately following fielding of the weapon system and an integrated R&M data system form the basis for analysis.

4. Data Requirements to Support Maturation Development

The second section showed that, with high-tech electronic components, actual R&M performance can fall far short of designed R&M performance. High-tech components are extraordinarily difficult to maintain. As noted, they suffer from deficiencies in fault detection, fault isolation, and fault removals. An R&M performance shortfall has serious consequences both for support costs and for operational capability. The overall objective of maturation development is to provide the designed R&M performance at lower life cycle costs. It pursues this objective through two approaches. One is to identify and correct R&M design deficiencies--particularly maintainability deficiencies--as early as possible in the development cycle of the weapon system. The other is to identify and remove lemons as they develop. The ability to capture and link data from different time periods, from different systems, and from different sources is needed to implement the maturation development process through each phase of the weapon system life cycle.

This section first describes specific capabilities that are required for the implementation of maturation development. These capabilities are based upon the availability and use of a database that is integrated over time, across functions, and across echelons. The required capabilities are contrasted briefly with the capabilities of two of the best current R&M data systems employed by the Services. The section then outlines the specific data elements required to support maturation development and closes with suggestions on reducing the costs and burden of collecting and integrating data.

Capabilities Required to Implement Maturation Development

The maturation development concept highlights the need for a number of capabilities in order to identify and eliminate maintainability design problems and lemons. These include the following capabilities:

- Assess R&M performance accurately.
- Identify patterns and sources of R&M anomalies.
- Evaluate effects of potential fixes on weapon system availability.

- Diagnose ambiguous faults.
- Identify lemons.

All of these capabilities require the development and use of an integrated database that facilitates the analysis of sequences of events. Such a database would also support other important capabilities, such as the following:

- Provide management reports.
- Schedule periodic maintenance efficiently.
- Support manpower estimation and spares requirements determination.

Each of these capabilities is described below, followed by a discussion of the integrated database itself.

Assess R&M Performance Accurately

In order to manage the R&M performance of a weapon system effectively, it is essential to have the capability to assess R&M performance accurately. This entails being able to measure the true reliability, the true maintainability, and the true logistics supportability of the system. Once these are known, the weapon system availability can be calculated for a specified mission. Measuring the true reliability and maintainability requires detecting and reporting all indications of R&M anomalies, including fault observations by the weapon system operators. Because maintainability concerns the existence of faults that repeat after a maintenance action, anomalies must be identifiable when possible by component serial number. Measuring logistics supportability requires data on administrative and transit times.

Identify Patterns and Sources of R&M Anomalies

Because high-tech components frequently display anomalies that are ambiguous, it is essential to have the capability to identify patterns of R&M anomalies in order to improve the diagnosis of problems. Establishing patterns requires being able to link data from different times, functions, and echelons. In addition, it should be possible to link R&M performance data with data regarding the operating environment and the mission. Some anomalies may manifest themselves only under special operational or environmental circumstances (e.g., extremely cold weather). A full picture of the performance history of high-tech components supports the development and testing of hypotheses regarding the source of anomalies.

Data should be integrated over time, beginning early in the development cycle. Information obtained in the research and development phases can be of use in later time periods for diagnosis and analysis if it is captured in forms that are appropriate. Plans for later use of the data must recognize that different functional systems will be used in later time periods. For example, the information on failures of prototypes is currently captured in manufacturing data systems for use by engineers in the identification and resolution of manufacturing problems. This same information may be useful later in developing an understanding of the frequency and occurrence of failure modes in later periods. Engineering may correctly conclude that a particular failure mode is an isolated instance in manufacturing, but knowledge of its occurrence is needed later to understand how it could relate to failures if it turns out that field conditions trigger this failure mode.

Once a system is fielded, maintenance data should be integrated across echelons. For example, the database should permit a maintainer at an intermediate level to learn whether fault detection and fault isolation results from his or her tests confirmed the symptom observed at the unit level that led to the removal. Likewise, the database should also permit a depot-level maintainer to determine whether depot fault detection and isolation results were consistent with the intermediate results. Such confirmations are needed to link corrective actions to observed faults.

Evaluate Effects of Potential Fixes on Weapon System Availability

Once the source of an R&M problem has been identified, alternative potential fixes can be developed and evaluated in terms of their relative costs and effects on the availability of truly FMC weapon systems. An integrated database can support the assessment of potential fixes by providing baseline performance data—data that can be used to help estimate the effects of alternative fixes.

Once potential fixes have been evaluated, ECPs can be developed and implemented when found to be affordable and cost-effective over the remaining fielded life of the weapon system.

Diagnose Ambiguous Faults

As noted in previous sections, high-tech components frequently present anomalies that are ambiguous. One of the strategies of maturation development is to greatly reduce such ambiguity by analysis of more data than are currently available. In addition to using the database to provide the capability to correct

hardware/software deficiencies prior to full-rate production, it could be used through the life of the system as a diagnostic tool. Ideally, a successfully run modification program would eliminate all ambiguity in fault detection and fault removal; unfortunately, it is unrealistic to expect that degree of success. In fact, a solution to the ambiguity problem may be to use an integrated database and improved maintenance procedures to isolate faults.

Identify Lemons

The source of an R&M problem may lie either in the weapon system design (broadly construed to include the design of a component, test equipment, operating or maintenance procedures, and training) or in the anomalous behavior of an individual component–a lemon

The key to identifying lemons is to collect and analyze operational and maintenance data by component serial number. If this is done, each individual component's contribution to operational capability and to the support burden can be calculated, and those components whose R&M performance is chronically poor can be identified and corrected, perhaps even removed from service. Once identified, lemons can be subjected to a special fault isolation program and then fixed or disposed of. A special fault isolation program is needed because components with such high removal rates generally have problems that cannot be detected or isolated using standard diagnostic testing schemes. They require engineering tests based on their particular symptoms.

Provide Management Reports

The reporting structure provided by the integrated data system can directly support managers. Such a structure must support two different kinds of reports:

1. Those that occur at regular intervals and give a picture for management and control of the R&M status and prioritized R&M problems of the weapon system.

2. Those reports, available on request, that allow analysis and investigation of the linkages, patterns, and probable causes of R&M performance shortfalls that require action.

This is in sharp contrast to most R&M data systems today that require a separate study into the possible causes of the problem as it surfaces. An engineering study of the situation will still be required to develop and evaluate alternatives,

but such study can begin with a clearer picture of the area for investigation and possible areas that are associated with the problem.

Schedule Periodic Maintenance Efficiently

The integrated R&M data system can be used to evaluate potential changes in scheduled maintenance for improved R&M performance as well as for potential cost avoidances. For some components--such as time between overhaul (TBO) items--there are periodic maintenance actions that interact with modification work orders in the fielded fleet. While the safety aspects of these are closely tracked today, there is little linkage to other effects, such as availability of the weapon system and impacts on sustainability. To maintain this linkage, reliability and maintainability budgets need to be maintained and updated to allow understanding of the related importance of problems and their impact on the weapon system cost and R&M performance.

Support Manpower Estimation and Spares Requirements Determination

Current data systems and spare/replacement parts requirement determination processes assume that the R&M problem is a one-time problem: That is, optimal repair level analyses are conducted once. These set the logistics parameters that drive the spares requirements determination processes. Once these parameters are set, item managers use historical data to determine buys, repairs, and distributions. An integrated database can help improve such decisions. R&M data are critical in determining the logistics resources required (e.g., spares) and controlling the application of those resources.

Capabilities of the Best Existing Databases

Among the data systems for current fielded systems, there are no examples of fully integrated R&M databases of the sort needed to support maturation development. However, a few existing data systems include significant elements of such a database. Two examples are the Army's data system for the TADS/PNVS system for the Apache and the Air Force's TICARRS (Tactical Interim CAMS [Core Automated Maintenance System] and REMIS [Reliability and Maintainability Information System] Reporting System) data system for the F-16 and F-15E fighter aircraft.

These are both contractor-operated data systems that generate information for project and logistics management for these weapon systems. The TICARRS data are gathered using remote terminals and the Air Force base data systems. The TADS/PNVS data are gathered using remote computers. Both systems cover maintenance at the end item, intermediate maintenance, and depot maintenance. Serial number data for LRUs and end items (e.g., tank or helicopter) are captured so that the data can be used to follow maintenance history at the end item, the configuration and modification status of the end item, subsequent maintenance events on removed components (serialized), and summary of events at each level of maintenance. This coverage across the fleet, across maintenance echelons, and linked to the initiating event is an important element of the integrated data system discussed above.

In other areas these examples of the best current practice are less complete. They do not capture anomalies that are observed but do not require maintenance. They capture only limited information on the operation of the equipment: operating hours between maintenance events for the Army system and operating hours for each mission, and number of missions for the Air Force. Data on test results are limited to entries in text fields and are frequently not entered. The use of test result data is limited by the absence of dictionaries to relate the test results at different test levels.

Data Elements Needed to Support Maturation Development

To this point we have described the capabilities of an integrated database to support maturation development. This subsection describes and illustrates the specific data elements that would be collected in the integrated database associated with maturation development. The data elements are summarized in Table 4.1. They fall into five major categories:

- Data associated with the weapon system at the unit level.
- Data associated with intermediate repair.
- Data associated with depot or contractor repair.
- Data associated with TMDE.
- Data associated with administrative and transportation processes.

The discussion focuses on data to be collected after the fielding of the system. The integrated database would also carry forward data from earlier phases (engineering and ILS development).

Table 4.1

Data Elements Needed to Support Maturation Development

Data Associated with the Weapon System at the Unit Level	Data Associated with Intermediate Repair	Data Associated with Depot or Contractor Repair	Data Associated with Diagnostic Test Equipment at All Levels	Data Associated with Administrative and Transportation Processes
For unscheduled maintenance	Date and time in work	Repair data	Operating time	Turn in date and time of failed items
• Symptoms in operation, including	Time on test equipment	Date and time in work	Confidence test time	Shipping date(s) and time(s)
– Comments	Test indications of faults	Test results	Diagnostic test time while troubleshooting	Nodal times in the transportation system
– Date and time	Time to repair	Components replaced (including serial numbers if appropriate)	Repair time for test equipment	Movement times
– BIT indications	Maintenance done	*Maintenance* performed	Parts used (with *serial numbers* where applicable)	Arrival date(s) and time(s) in the supply system
– Operational context	Date and time the repaired item is available	Awaiting parts time	Test equipment adaptors	Date and time to maintenance in the supply system
• Maintenance test results		Date and time available	Software	Date and time from maintenance (both order and ship segments and retrograde segments)
• Maintenance performed			Test equipment configuration	
• Items replaced				
• Serial numbers				
• Operational time for installed and removed items				

Table 4.1—continued

Data Associated with the Weapon System at the Unit Level	Data Associated with Intermediate Repair	Data Associated with Depot or Contractor Repair	Data Associated with Diagnostic Test Equipment at All Levels	Data Associated with Administrative and Transportation Processes
For scheduled maintenance: • Date and time • Maintenance performed • Items replaced • Test equipment data *including* – Usage and operating time – Maintenance – Items replaced				

Data Associated with the Weapon System at the Unit Level

The first set of elements is associated directly with the weapon system components at the unit level (frequently a part of organizational maintenance). For unscheduled maintenance, these include (1) symptoms in operation, such as comments, date and time, BIT indications, and the point in the operational sequence when the anomaly occurred, and (2) maintenance test results, maintenance performed, items replaced, serial numbers and operational time for the installed and removed items, and identity of maintainers.[33] The data system should also capture operational anomalies (i.e., those reported by operators) when no maintenance was requested or performed so that recurring anomalies can be identified. Linked to this data should be information about scheduled maintenance--e.g., date and time, maintenance performed, identity of maintainers, and items replaced with above detail. Also linked to these elements should be data on the test equipment (if any) used at the unit level--e.g., usage, operating time, maintenance actions, and anomalies with test equipment.

Data Associated with Intermediate Repair

The second set of data elements for R&M is associated with intermediate repair. Data captured here are on items removed from the end items and on components used in the repairs. The data collected are date and time in work, the test time on test equipment, test indications of faults, the time to repair, maintenance done and parts used, identity of maintainers, awaiting parts time, sell-off test time,[34] and the date and time the repaired part is available. These elements need to be linked to the unit-level data listed above.

Data Associated with Depot or Contractor Repair

The third set of data elements comprises those that are available at the contractor or depot. These include repair data such as date and time in work, test results, components replaced (including serial numbers where applicable), maintenance or repair performed, identity of maintainers, awaiting parts time, and date and time available. Overhaul date and associated removals should also be included.

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[33]We recognize that data on individual maintainer performance are sensitive. Nevertheless, we advocate its collection because it may be useful in identifying maintainers who are especially successful in diagnosis or repair. The expertise of such individuals may be studied and important lessons learned can be incorporated into training or doctrine.

[34]The time it takes to confirm that a repaired component is in fact repaired (i.e., ready to be "sold off" again).

Data Associated with TMDE at All Levels

The fourth set of data focuses on diagnostic test equipment at all levels. TMDE capacity has an important impact on weapon system sustainability. These data should include operating time, confidence test time,[35] diagnostic test time while troubleshooting the test equipment itself, repair time for the test equipment, parts used with serial numbers where applicable, and test equipment adapters, including software and test equipment configuration.

Data Associated with Administrative and Transportation Processes

The fifth set of data elements focuses on an integral part of the maintenance process, the administrative and transportation processes used in the support system. Data elements include turn-in date and time of failed items, shipping date and time, nodal times in the transportation system, movement times in the transportation system, arrival date and time(s) in the supply system, date and time to maintenance in the supply system, and date and time from maintenance. These data elements should cover both the order and ship segments and the retrograde segments.

Lessening the Cost and Burden of Data Collection

Extensive data must be collected to capture the information required to identify and manage R&M problems of high-tech, high-cost LRUs. Data about high-tech subsystems need to be captured in detail; existing data about weapon system operation (in the form of log book data) need to be integrated with other data so that they can be accessed and used. Because data collection and analysis is expensive, collecting detailed data on every item of a weapon system may not be economically feasible.[36] A comprehensive integrated data system may be justifiable only for selected high-tech subsystems of important weapon systems. Research is needed to establish the requirements for detailed data collection and to determine methods of collection and integration that are affordable.

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[35]The time it takes to test the TMDE itself to confirm that it can be used with confidence to test a suspected bad component.

[36]Some of the expense can be spread across weapon systems. For example, the information systems to support lemon detection, while costly, could be designed so that they need be implemented only once for the Army maintenance system. After providing the capability to collect and analyze such information, that capability can be used virtually free for all later acquisitions.

Technology can be used to reduce both the cost of collecting data and the burden on the maintenance and operations personnel. Ideally, if an item is serial numbered it would be tracked in an integrated database. However, as a practical matter, the lack of automated data collection prohibits collecting data on all serial numbered items. Many of the data required for analysis could easily be made available in today's high-tech systems but are not being captured. Simple technologies, like recording devices, could be used. Just now being developed are "smart chips" that can be built into circuit boards and perform logical diagnoses of the board to which it is attached and store and transmit that data to the next higher assembly. Such a "bottoms up" design of LRUs and subsystems would ensure the capture of adequate information for all levels of maintenance and engineering. This process would allow technicians to capture the information by direct access to the chip, SRU, or LRU without need for additional recording devices.

Physical data capture mechanisms should be designed to feed automatically into the integrated R&M management system in order to reduce the burden on the operators and maintainers and provide the necessary information for R&M fixes. The data systems must be designed to capture the physical structure of the data and their logical linkages. The physical structure must include data from all echelons, from occurrence of the fault through final removal of the fault. The logical linkages must be present in order to ensure that each removal and repair action is logically connected to a reported fault.

5. Implementation of Maturation Development

In this section we discuss briefly some of the actions that can be taken by the Army now to improve the availability of FMC weapon systems. We start by reviewing steps proposed in this report to improve the availability of weapon systems that are in the early stages of research and development. We follow that with a discussion of what steps can be taken now to improve the availability of fielded high-tech weapon systems. We note the necessity of taking early action to manage high-tech R&M performance. Acting early makes it possible to justify the costs of the maturation development process--including potential engineering modifications--in terms of direct support savings over the life cycle of the weapon system. We conclude by addressing various obstacles--technical, environmental, and organizational--to implementing maturation development.

Applying Maturation Development to New Weapon Systems

It is important to emphasize that high-tech weapon systems will have R&M problems when first fielded, problems that cannot be completely obviated even by the highest-quality design and production. Key decisionmakers attuned to this fact will seek to determine whether the inevitable R&M problems are consequential and if they can be solved.

We have proposed a concept, maturation development, for identifying and fixing the R&M problems associated with new high-tech weapon systems. This concept should enable program managers to reduce the risk of acquiring weapon systems that are not affordable or sustainable over the life of the system. The concept proposes that the program manager design the hardware from the beginning so that it can be easily modified to correct deficiencies found in later stages of development. To track the performance of that design, an integrated data system is established to capture relevant data and link the design to past and present data and data yet to be collected. A key step of this concept is an intensive data collection phase that occurs during LRIP and is used to identify and analyze deficiencies. The data collected from this and previous phases will permit a comprehensive analysis and identification of alternative solutions prior to full-rate production. Improvements to fault detection and isolation systems should

be easily accommodated because of the design architecture used in the earlier phases of the program. Continued monitoring of modifications and fielded weapon systems should be automatic and at far less of a burden to operators and maintainers than current systems.

Current legislation and DoD direction establishes a critical role for the Assistant Secretary of the Army for Research, Development, and Acquisition (SARDA) in this process. As the Service acquisition executive, he is responsible for establishment of acquisition policy and review of programs for advancement through the acquisition process. In Section 2 we presented much evidence from studies of high-tech systems indicating a considerable amount of risk associated with the R&M of high-tech weapon systems. As a means of reducing program risk, the SARDA could establish a policy requiring that program managers identify, in their periodic reviews, any process or system they have to manage these risks. (Currently, managers have little incentive to highlight R&M risks after the selection of system alternatives that occurs in the demonstration/validation phase, when technical risks and economic uncertainties are identified.) The program manager could reduce the R&M risk by using an integrated data system in conjunction with an intensive data collection period such as that described in Section 3.

A second policy that could be implemented relates to the criteria used to evaluate a weapon system's readiness to move to full-rate production. Currently, measures such as mean time to repair are used to assess a system's maintainability.[37] A measure such as "fault removal efficiency" that captures the effectiveness of fault detection and reporting as well as fault isolation is more meaningful. This measure could be reported at the production decision milestone. Means to measure this value would need to be incorporated into the testing program.

Given the current acquisition environment, the Army can expect to develop and field few major systems in the 1990s. Nevertheless, if policies such as these were implemented now, the Army would be in a position to apply maturation development to those new systems that it does have some prospect of acquiring, such as the Comanche and the Longbow.

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[37] While of some value, these measures have many limitations. Actual time to repair an LRU is determined by factors such as spares availability and test equipment availability. A full discussion of current maintainability measures is provided in Gebman et al. (1989).

Applying Maturation Development to Fielded Weapon Systems

Maturation development as described in Section 3 of this report addresses new systems that are in research and development; yet the Army is more commonly faced with the upgrading of weapon systems that are already fielded. Some of these modifications are large and complex enough to justify maturation. Fortunately, maturation development can be adapted for application to fielded systems. The maturation development concept relies on data collection and integration, followed by problem identification and analysis, which leads to alternative development and evaluation. These activities can apply to improving the R&M performance of fielded systems as well as new ones.

As the DoD enters a phase of reduced spending on new acquisitions and greater interest in upgrading existing systems to meet new requirements, an opportunity exists to mature the design of these fielded systems. The Army could start now by taking actions such as the following:

- Collect data identified in Section 4 on the high-tech systems of deployed weapon systems (such as the fire control subsystem of the Apache, the mast mounted sight on the Kiowa, the electrical section of the launcher-loader module on the Multiple Launch Rocket System [MLRS], and the fire control system on the M1A1 tank).
- Analyze the data to determine the true fault removal efficiency of these systems and to identify the most troublesome R&M deficiencies. Such an analysis could be used to identify fault detection, fault reporting, and fault isolation problems as well as lemons.
- Develop engineering fixes to these problems and mature them in the development process.

The Army should also consider applying maturation development to any fielded system that meets these criteria:

1. It is scheduled for a major upgrade.
2. The upgrade involves high-tech electronics suites (usually the case with major upgrade programs).
3. The upgrade will apply to enough of the fielded fleet (a) to permit the collection of adequate data during the maturation development phase and (b) to justify the cost of the maturation development program.

To the degree that the proposed electronic suite relates to the existing suite, the data on the fielded systems may be used. The use of block improvements and thorough testing using "test bed" weapons are certainly consistent with the maturation development concept.

More specifically, the Army could test the maturation development concept on a fielded system by applying it to the upgrading of the fire control system of the Apache. Unlike the case of the Air Force with the F-15 and F-16, the Army may not need to conduct a special data collection effort on the Apache to identify and isolate the sources of R&M performance degradations. The contractor, Martin Marrietta, maintains an extensive database that, though not sufficient to support application of the maturation development concept, contains many of the data above, including some operational data on anomalies at the end item.

Obstacles to Implementing Maturation Development

Maturation development has been advocated by RAND since the mid-1980s. The logic and evidence proffered in support of the concept have been widely accepted. Why, then, has maturation development not been implemented in any of the Services' major acquisition or upgrade programs? There are four kinds of *obstacles to implementing maturation development*: cost obstacles, technical obstacles, environmental obstacles, and organizational obstacles.

Cost Obstacles

One obstacle to the implementation of maturation development is that program managers are reluctant to add activities (costs) when they are unsure of the savings; moreover, even if they believe that savings will accrue in the long term, over the life of the system, they may be unwilling or unable to implement additional activities that increase costs in the short term. Costs associated with maturation development are basically of two sorts: the costs of developing, maintaining, and using an integrated data system (including the costs of the intensive operation and data collection and analysis that occurs before full fielding) and (2) the costs of developing and acquiring new component designs that offer improved R&M performance.

To our knowledge, no analyses to date have calculated the savings in support costs that could have been achieved through the use of an integrated database to improve the performance of the maintenance system. Several programs, however, offer evidence regarding the cost savings to be achieved through component redesign to improve R&M performance.

In the 1960s, the Air Force redesigned the missile guidance subsystem for the Minuteman I, improving its MTBRs from 600 hours to 9000 hours. This development effort cost $150 million but saved $1.5 billion in life-cycle support costs. It also increased the availability level of the missile from 70 percent to over 95 percent.[38]

The Army's Hawk missile system included a successful effort to improve the availability/resource unit cost ratio. The Hawk program had R&M problems with the high-power illuminator, which the sample data collection system indicated had a mean-time-between-failure (MTBF) rate of 43 hours. In 1979 the program spent $10.7 million for research and development of a modified unit. The production of the modified units cost another $164.5 million in 1982, and the training and installation in 1985 cost another $21 million. The savings in replenishment spares was estimated at $34.4 million per year. The costs and dollar benefits, discounted at 10 percent per year, were about equal. More important was the increased availability achieved by increasing the MTBF from 43 hours to 134 hours and the additional benefit of a range improvement of 20 percent. Increases in availability are rarely considered in these analyses because of the difficulty in putting a dollar value on them.[39]

The Air Force experience in applying elements of the maturation development concept to the F-15 and F-16, as indicated in Section 2, was less successful. This experience suggests that if the component design problems are not identified early enough, the dollar costs to incorporate only the maintainability modifications generally outweigh the costs to continue to support deficient weapon systems logistically. The Air Force conducted separate studies of the F-15 and F-16 after they were fielded to obtain the data needed to correctly identify the problems discovered during operation. In an effort to reduce the costs associated with the maintainability problems, the program managers for both weapon systems developed ECPs. In the case of the F-16, the program manager sought redesign of the LPRF LRU, and in the case of the F-15, the program manager sought replacement of the BIT system. In both cases, the cost to develop new systems was about $25 million but to retrofit the existing faulty systems fleetwide would cost another $200 million. As a result, neither modification was judged to be justifiable on the basis of operating and support costs (despite the potential improvement to the availability of FMC systems), and the modification efforts were abandoned.

The Army can learn an important lesson from the Air Force's experience—namely, that it is imperative to begin R&M maturation efforts as early as

[38]See Gebman and Shulman (1988).

[39]Based on unpublished information from U.S. Army Missile Command (17-19 July 1991 visit).

possible, not only to maximize any potential support costs savings over the life cycle, but to be able to realize savings sufficiently large enough to offset the costs associated with a maturation development process and associated engineering modifications.

The Air Force's inability to justify these modifications raises the issue that new ways of measuring the costs and benefits of improving high-tech R&M performance should be considered. Simply comparing the cost of a modification with the cost of logistically supporting a deficient system does not capture the cost and risks of living with a deficient system, in terms of lost weapon system capability or lost weapon system availability, or the benefits of truly mission capable systems. Further, as the U.S. military moves to keeping weapon systems longer and moves to a CONUS-based force, the costs of logistically supporting from afar need to be strongly considered. Likewise, the benefit of being able to deploy fewer truly mission capable weapon systems needs to be captured in such an analysis.

Technical Obstacles

The chief technical obstacle to maturation development is the need to adopt a *new conceptual framework for* understanding and managing R&M performance of high-tech systems--what an earlier RAND report called the need for "a new view of weapon system reliability and maintainability."[40] This new view must focus on the inherent complexity of Type B faults compared with Type A faults and the implications for data collection, analysis, and measures of R&M performance.

The difficulty of observing Type B faults stems from their dependence on a larger set of conditions in operational time sequences. These dependencies mean that large sample sizes are needed to identify and solve these faults. Type B faults must be identified through their recurrence in a sample rather than being identified by a single static maintenance check as are Type A faults. Without a large sample size, individual anomalous events may be too readily ascribed to "noise."

Another related technical obstacle to maturation development is that special testing data will often be required to diagnose the cause of a Type B fault. Indeed, collecting such data is one of the purposes of the intense period of operation data collection and analysis. However, all data that may be needed on

[40]Gebman et al. (1989).

occasion need not be collected all the time. The data collection system can be designed to permit specific data to be targeted for more detailed collection after an anomaly has been observed.

Lack of appropriate measures is another obstacle. New measures of R&M performance are needed because the current measures were developed at a time when easily repeated Type A faults dominated the R&M problem. These measures do not attempt to define and measure the occurrence of Type B problems. For example, MTBF is a good measure of Type A problems in a power supply rectifier when the failure means no power, but it is not useful for Type B problems--for instance, degradation that arises because in some operational modes the power supply generates substandard output.

Configuration control is also a technical obstacle. A system obviously must undergo design changes as problems are uncovered and resolved during testing. Unfortunately, the effect of the changes on complex Type B faults is difficult to evaluate because of the necessarily limited testing and the cumulative or interactive effect of the changes. As changes are introduced, they act in combination both to change system behavior by removing and introducing. These combinations introduce new configurations that in turn reduce the sample size per configuration in the data collection.

Given the developments in data processing and the potential for onboard data capture in operation, the technical limitations of data integration and management appear much less serious now than even a few years ago. Unfortunately, the lack of measures to indicate the extent and cost of these problems in fielded systems have limited the appropriate application of such technology. Lack of a perceived need has limited the automatic collection of data from databuses, the introduction of programmable data collection using such buses, and the use of R&M programmable databuses.

Environmental Obstacles

When maturation development was first developed in the 1980s, a major obstacle to its adoption was the acquisition environment of the Cold War era. When the U.S. faced a very strong Soviet threat, weapon systems were designed, developed, and fielded very quickly because their superior capability was needed to overmatch the latest generation of Soviet systems. Maturation development was resisted because it would require additional activities preceding full-rate production and these activities could delay fielding by as much as a few years. Although these activities would increase true weapon system availability of fully capable systems, improve system R&M performance,

and reduce life-cycle support costs, it was deemed more prudent to field weapon systems that were not fully mature in terms of their R&M performance. The relative R&M immaturity of these systems drove up their support costs, but these cost increases were accepted as part of the price of security in the Cold War.

Today the national security environment is radically different, and in at least two respects it has become much more conducive to the application of maturation development. First, the chief motivation for highly compressed acquisition programs has disappeared because the United States is no longer in an intense arms race with the Soviet Union. Second, because acquisition budgets have been greatly reduced, there will be more inclination to upgrade an existing system than to acquire a new one, and significant upgrades present the opportunity to mature the R&M performance of the design as well as its mission capability. When weapon systems can undergo a more deliberate acquisition process and when existing systems undergo significant upgrades, time to mature the design is available. Third, because of budgetary pressures, the concern with reducing total life-cycle support costs has increased. For all of these reasons, maturation development should appear much more attractive in the current acquisition environment.

On the other hand, some features of the new environment may still act as obstacles to the implementation of maturation development. For one thing, there are likely to be few new program starts and thus few opportunities for applying maturation development to new weapon systems. Second, a few acquisition programs may still be highly compressed--for example, if they are developed in response to a new and unforeseen technological threat. Third, some acquisition programs may involve very small production runs--perhaps well below 100 weapon systems--as with the F-117 stealth fighter and the B-2 stealth bomber. When such small fleets of weapon systems are acquired, it may not be possible to justify some features of maturation development, such as the use of an intense period of operation, data collection, and analysis before full fielding. Sufficient data may only be generated when the entire fleet is operational.[41] The most common use of maturation development in the post-Cold War era will probably be to improve the R&M performance of major fielded weapon systems scheduled for a significant upgrade.

[41] A detailed discussion of the utility of maturation development under three possible acquistion regimes in the post-Cold War era appears in unpublished RAND research by Frank Camm and Hyman Shulman.

Organizational Obstacles

A major source of obstacles to implementing maturation development is the need for diverse organizations--both organic and contractor--to change their activities and their interactions.

For example, one organizational obstacle to the implementation of maturation development is the need to include in development planning the time and resources for a period of intensive operation, data collection, and analysis. Changing development planning in this way requires the government to acknowledge that there will be R&M problems that lie outside the contractor's development efforts. This conflicts with the widespread belief that the prime contractor is responsible for all system phenomena whether or not they are included in the system testing. This belief persists despite the absence of examples where such responsibility has been imposed on a prime contractor (i.e., cases where the prime has been held responsible for complex R&M problems that result in fleet degradation and life-cycle cost increases, as opposed to cases of a properly functioning component failing to perform to specification). In fact, such general, implied responsibility is inappropriate given the complex interdependency of responsibility in the approval and execution of numerous design changes during a system development. Sole contractor responsibility must necessarily be limited to areas where there is a clear mutual understanding of the responsibility and an appropriate means of pricing that responsibility.

Another organizational obstacle is the split between the procurement and support organizations. Maturation development requires the closer integration of these functional stovepipes. Currently, just at the time that a large sample of data from fielded systems becomes available, the major responsibility for the support and cost of support is supposed to move to the major supporting command and depot community. The procurement project office understandably feels that it has completed its job, and the depot community is occupied with assuming engineering, budgeting, and repair responsibility. The traditional focus of program managers has been to field an effective weapon system on schedule and within budget. The measure of "effective" has usually been the ability of the weapon system to perform its missions. And the budget concern has generally been limited to allocated dollars (current year) or dollars to be allocated to complete the development and to acquire the required quantity. Future costs are, arguably, difficult to measure. Maturation development is concerned with providing sustained availability of FMC weapon systems and reducing total life-cycle costs. This can be accomplished when acquirers and logisticians recognize the up-front costs and the life-cycle benefits of a maturation development approach. The maturation development approach calls

for time and dollar resources to mature the design, the requirement to manage R&M risk, and "fault removal efficiency" as a milestone criterion.

Underlying organizational difficulties are the complexity of the Type B problems and the lack of appropriate measures. These problems require a team approach that is very difficult to achieve in an organization of separate functional groups with separate functional responsibilities. In such organizations, integration across the functions to solve a complex problem does not take place when it is not perceived to affect the performance measures by which the groups are evaluated. For example, maintenance technicians currently are measured on the number of units that they restore to operation. Components that show NEOF are considered repaired and count as a "restoration." Although nothing was repaired and the maintenance activity was minimal, maintenance technicians receive as much credit as though they consumed 10 times the resources to restore a truly broken component. Maturation development would call for measures that incentivize true-fault removal efficiency, i.e., where a fault is only considered removed after the component has been proven to function properly in its operational environment. If an NEOF occurred and the component repeated as a failure, maintenance technicians would seek to identify the cause of the NEOF.

Conclusion

This report has demonstrated the following points:

1. High-tech systems have fault detection and fault isolation problems when first fielded.
2. Lemons develop over time.
3. These problems cause an excessive burden on the logistics structure.
4. The availability of truly mission capable weapon systems is probably overestimated by current data systems.
5. A concept for "maturing" the R&M performance of high-tech weapon systems is needed.
6. Elements of such a concept, called maturation development, have been tested by the Services and found to be promising.

Underlying the maturation development concept are several hypotheses (1) fault detection, reporting, isolation, and removal can be improved through the use of an integrated data system; (2) component design problems that degrade R&M performance can be identified with sufficient information; and (3) component

designs with improved R&M performance, if proposed early enough in the acquisition process, warrant the dollar cost to implement them. These hypotheses apply both to the acquisition of new weapon systems and the acquisition of major upgrades and modifications.

We predict that the need for maturation development will increase. The need to achieve required weapon system availabilities at lower costs is evident throughout the Army. Evidence from both Army and Air Force high-tech weapon systems points to serious diagnostic and repair problems, as well as the existence of lemons. All evidence suggests that R&M immaturity is directly correlated with technological complexity. Therefore, the Army can expect to discover increasing R&M problems as its inventory of weapon systems, both through upgrades and new procurements, becomes increasingly sophisticated technologically.

Using current methods, the cost of keeping the same high levels of availability for the most sophisticated Army weapon systems that we have enjoyed in the past is prohibitive. While many approaches toward achieving an improved "availability per unit resource cost" are possible, we argue in this report for improving the maintainability of the weapon systems. Improvements in maintainability through maturation development offer the twin benefits of increased availability of fully capable weapon systems and lower total life-cycle support costs.

Appendix

Weapon System Sustainment Management

This appendix summarizes a concept for revolutionizing the Army logistics system. The concept, called Weapon System Sustainment Management (WSSM), has been developed at RAND in conjunction with senior Army logistics leadership. The WSSM concept synthesizes the results of a very large body of logistics research conducted by RAND over several decades for the Services and the Office of the Secretary of Defense. Maturation development is an approach for implementing one of three strategies in support of WSSM.[42]

The Need to Revolutionize the Army Logistics System

The current logistics system was designed to support a massive European war. With the end of the Cold War, the U.S. military is being downsized and reshaped to meet the requirements of a new era in which military power will need to be projected from the CONUS to any number of contingencies around the world. To meet the support needs of the Army in this new era, the Army logistics system must become leaner, more flexible, and more responsive: leaner because defense budgets will no longer enable the Army to maintain a massive logistics system; more flexible because the Army must prepare for a wide range of potential contingencies rather than focus on a major European case; and more responsive because of increased uncertainty regarding the nature of the threat and because neither forward positioning nor host nation support can be assumed. Figure A.1 suggests schematically how the future Army logistics system will differ radically from the current massive system.

The envisioned changes are so great that one might question whether they are even feasible. However, there are grounds for optimism.

[42]For a fuller discussion of WSSM, see J. Dumond et al., *Weapon System Sustainment Management: A Concept for Revolutionizing the Army Logistics System, Annotated Briefing*, RAND, DB-104-A, forthcoming.

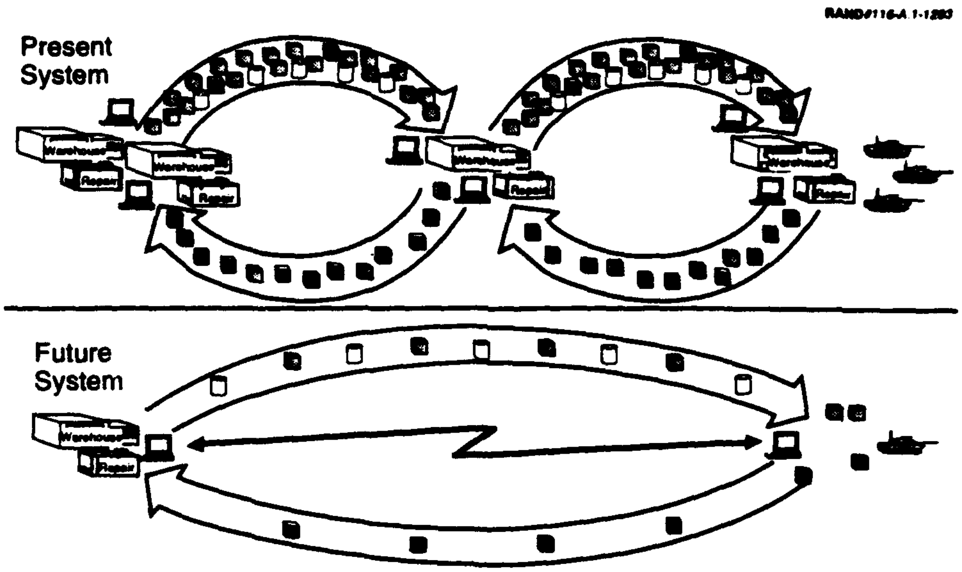

Figure A.1—The Army Logistics System Must Become Leaner, More Flexible, and More Responsive

Radical new management techniques have enabled the best commercial firms to become leaner and more flexible. On many measures--such as inventory, defects per unit, timely delivery, production lead time--these firms have achieved order-of-magnitude improvements of the sort that the Army logistics system must strive for. Many have argued that a new management paradigm is emerging. This paradigm is marked by an increased focus on the customer, the establishment of measurable, customer-related goals; the "reengineering" of processes to achieve the goals; and continuous product and process improvement. WSSM applies similar management strategies to improve the Army logistics system, as shown in Figure A.2:

- Focus the entire system on the customer's needs.
- Design and redesign weapon systems to be more supportable.
- Design and manage processes to be more responsive and efficient.

This appendix addresses each of these strategies in turn.

Focus the Entire System on the Customer's Needs

Currently managers throughout the Army logistics system rely on local measures that are not directly linked to a common system goal. For instance,

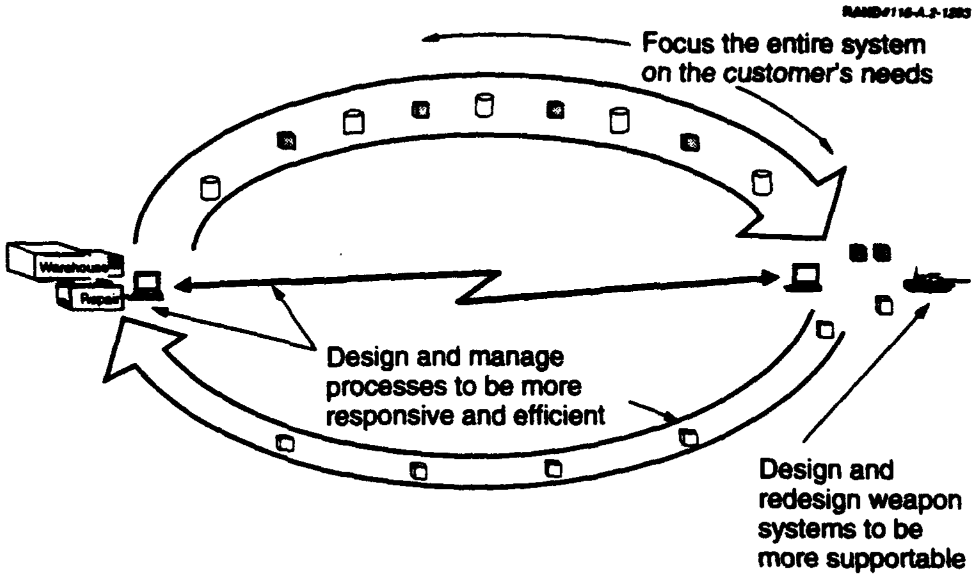

Figure A.2—Management Concepts Similar to Those Used by the Best Commercial Firms Can Improve the Army Logistics System

transportation managers may use a measure such as full truck load to assess the performance of their assets; likewise, repair shop managers may use a measure such as rate of labor or equipment utilization. These measures encourage efficient use of resources locally, but they do not provide any indication of whether a specific management action improves the efficiency and effectiveness of the logistics system as a whole. Successful commercial firms teach the importance of focusing on the customer. The customer for the logistics system is the operational commander who needs logistics support. More specifically, the operational commander requires sufficient weapon systems to perform the planned mission. The responsibility of the logistician is to manage the inputs (personnel, capital, materiel, information, etc.) and the processes (distribution, repair, etc.) of the logistics system so as to provide the sustained weapon system availability that the operational commander needs.

The logistician faces an additional challenge in attempting to provide this output at a time when logistics resources are being reduced. RAND is analyzing two fundamental ways to compensate for reduced resources: (1) reengineering logistics processes to make them more efficient and more effective and (2) making better use of information in support of those reengineered processes. Logistics managers require the capability to control resources effectively and the capability to assess the performance of the system so that the use of resources can be adjusted accordingly. The assessment capability permits logistics managers to

understand how their decisions affect the goal. A decision support tool for assessment is useful to managers in two ways. First, it permits them to anticipate problems in meeting the goals of the operational commander. For example, it might indicate that at a certain point in the planned mission the commander would not have available the needed number of weapon systems. Second, when problems have been identified, the same tool can be used to assess how alternative policies affect the performance of the system.

RAND has developed assessment tools for the Army and the Air Force. It developed an assessment tool called Dyna-METRIC for the Air Force, which has implemented it as part of its Weapon System Management Information System. RAND recently adapted the tool to the needs of the Army. The Army has field-tested a prototype of this version at the U.S. Tank-Automotive Command to assess support of the M1A1 Abrams Tank and the Bradley Fighting Vehicle. The Army and RAND have further experimented with using the tool to assess the support of systems in Somalia.

Design and Redesign Weapon Systems to Be More Supportable

Weapon systems create the burden on the logistics system. U.S. weapon systems are increasingly complex as more high-tech (largely digital) components are added to increase capability. Unfortunately, this added complexity in weapon systems also results in reduced availability and increased costs. As Figure A.3 illustrates, the added burden comes about in two ways. First, high-tech components and subcomponents do not usually fail outright but rather exhibit spotty and degraded performance. Such failure modes are hard to diagnose and isolate, with the result that maintainers often will remove, test, and repair several components--most of them good--in search of the faulty component. Second, a few individual components are lemons--that is, they are chronically defective and cycle through the repair system repeatedly. These lemons account for about half of the workload on subcomponents at their respective depot-level repair shops. Compared to a non-lemon component of the same design, a lemon consumes 20 times as many subcomponents. Both the fault isolation problems and the presence of lemons in weapon systems cause commanders to overestimate the number of available systems that are truly FMC.

During the Cold War, the United States had a strong rationale for fielding new weapon systems that were not fully matured in terms of their R&M. Their operational capability was needed to maintain a margin of technological superiority over the Soviets. This rationale has diminished in the post-Cold War

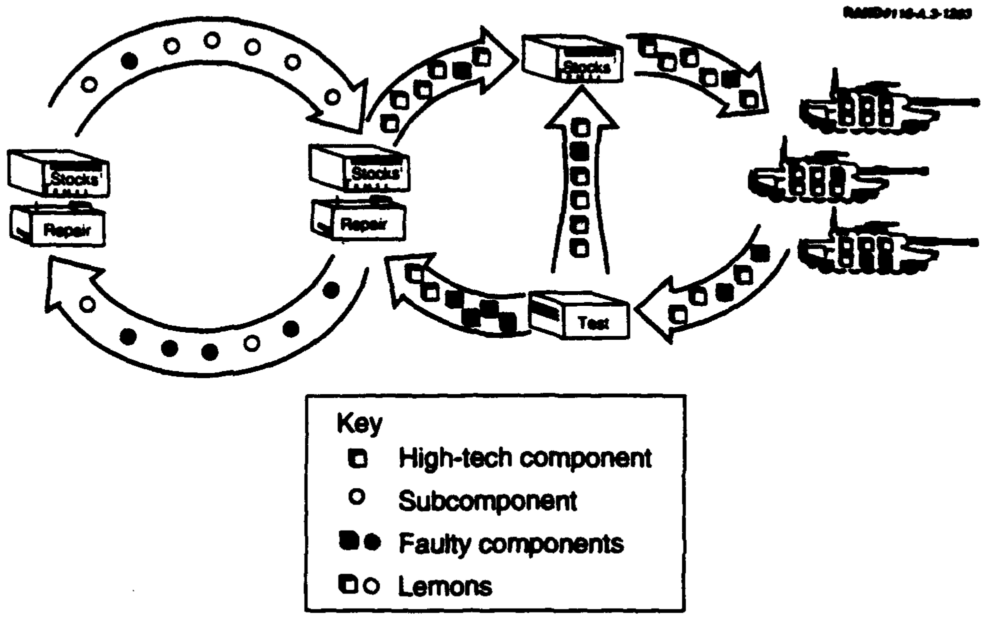

Figure A.3—More Complexity in Weapon Systems Results in Reduced Availability and Increased Costs

era, and the United States can now adopt a less compressed acquisition strategy that will permit complex weapon systems to be more fully matured before fielding, thus reducing their burden on the logistics system.

RAND has developed a concept for improving the sustainability of weapon systems in order to achieve increased weapon system availability at lower costs. This concept calls for maturing the design of newly developed weapon systems, particularly during the low-rate production phase, and identifying the lemons during the fielded phase. The key element of the approach is an intensive data collection and analysis prior to full-rate production. The approach calls for the design of the weapon system to be frozen during low-rate production so that a known design configuration can be operated intensely while data is collected and analyzed. Based upon the results of this analysis, the Army would modify the design of the weapon system to make it more mature and supportable. These improvements would lead to improved availability at lower costs throughout the fielded life of the system. To support the intensive analysis, a database would be established during the earliest phases of acquisition. This database would be integrated across time, echelons, and functions and would be sustained through the life of the system in order to identify additional design problems that may emerge due to aging effects or to mission changes.

The database would also be used to identify and remove lemons. These are high-tech components that exhibit chronic performance problems. Although such components compose about 9 percent of the total set, they are responsible for a very large proportion of the logistics burden and contribute very little to operational capability. These lemons can be identified through the use of a database that tracks components' operational and maintenance history by serial number.

RAND has recommended that the Army apply this concept to the Comanche and to the upgrade of the Apache. The recommendation for the Comanche emerged during a 1987 study of the Army's proposed new attack helicopter (then called the Light Helicopter Experimental). That study projected that just eight high-tech components in the avionics suite would account for 80 percent of the spares and repair costs and 70 percent of the system downtime. Maturation of these components was recommended to enable the program to achieve its performance and cost goals. Serial number tracking would also permit the culling of lemons.

Although the Comanche acquisition is delayed, the Army can gain experience with these concepts by applying them to the planned upgrade of the Apache. The concept is also applicable to fielded systems; however, because the application of maturation development affects component design, some of its potential benefits will be offset by the cost of retrofitting an existing fleet.

Design and Manage Processes to Be More Responsive and Efficient

As depicted in the top panel of Figure A.1, the current logistics system is too costly, slow, and inaccurate. As of the end of 1992, the DoD has over $80 billion in spare parts. Yet with all this mass, the system still is not responsive. In a study of support in Operation Desert Storm, RAND researchers interviewed unit-level commanders and logisticians who for months received no spare parts to bring out-of-commission weapon systems to mission-ready status—even though the supply system shipped massive stocks to the theater, including twenty-five thousand (25,000!) forty-foot containers whose contents were unknown. The system certainly did what it was designed to do—project a massive amount of materiel forward—but having mass does not necessarily provide the weapon system availability needed by commanders.

RAND is advocating a management concept called "velocity management" that aims to replace much of the current reliance on logistics mass to a reliance on the improved velocity, accuracy, and reliability of logistics processes. The

commercial sector has demonstrated that the speed, accuracy, and reliability of processes can be dramatically improved. RAND is analyzing ways in which Army--and DoD generally--logistics processes can be reengineered to achieve the same type and magnitude of improvements. The key is to remove non-value-adding activities and to improve the performance of value-adding activities.

With RAND's assistance, the Air Force recently conducted a field test that demonstrated how reengineered processes can lead to radical improvements. The Air Force "reengineered" the depot repair process for 32 high-value and very high-value components in 400 aircraft. The result was a 75 percent improvement in turnaround time for the high-value components (from 32 to 8 days) and an 81 percent improvement for very high-value components (from 32 to 6 days). The reengineered system saved millions of dollars per year and delivered the same performance as the old system.

Improved velocity of logistics processes reduces the need for expensive inventory. RAND analysis of Martin Marietta data associated with just one high-tech component of the Apache helicopter provides an example. The analysis showed that if the Army could increase the velocity of this component through the depot repair pipeline from about 90 to about 15 days, then it could reduce the value of stock in the pipeline from about $60 million to about $10 million (an 83 percent reduction).

These two examples from the Air Force and the Army illustrate process improvements on the same scale as those found in the best commercial firms. Logistics managers will need to use greatly reduced resources more efficiently and effectively. No longer will it be possible to rely on massive resources to cover uncertainty and risk. Logistics managers will need decision support tools to help them control reduced resources. Such tools will help a manager decide how to use available repair and supply resources so as to meet the needs of the operational commander in the most efficient manner. RAND has developed control tools for the Army and the Air Force. The RAND-developed control methodology, called DRIVE for the Air Force, is undergoing field testing at Ogden and San Antonio Air Logistics Centers. RAND also adapted the methodology to the Army's needs. The Army, which calls the system RBM or Readiness-Based Maintenance, has field-tested the tool at the U.S. Army Missile Command to control repair of the Multiple Launcher Rocket System. RAND has also developed another version of the tool that reflects the new DoD policy to increase the operational unit's incentives to reduce repair costs.

Conclusion

The management concept described here, Weapon System Sustainment Management, integrates much RAND logistics research. As we have indicated, RAND's experience with assessment tools (the Dyna-METRIC family) began with the Air Force and grew to include the Army as well.

Similarly, the maturation development concept has been developed through a series of studies addressing the needs of different Air Force and Army systems. RAND's experience with the DRIVE family of control tools also includes both Air Force and Army applications. Some of the examples of improved processes and streamlined logistics structures were developed in other RAND projects on modular logistics, alternative support structures, and alternative maintenance concepts. A current study on the Army distribution system is also contributing to the Weapon System Sustainment Concept. RAND's Weapon System Sustainment Concept is influencing DoD as well as the Army. The DoD is undertaking a thorough review of the existing logistics business practices in the Services with the goal of identifying improved processes that, to the extent possible, are standardized across Services. Then the DoD will mandate the development and implementation of standardized logistics information systems to support those improved processes. RAND has several projects ongoing for clients who are engaged in this activity (including the Army, Air Force, Navy, Defense Logistics Agency, Assistant Secretary of Defense for Production and Logistics, and the Director of Defense Information) and so is well positioned to contribute to its outcome. We believe that the Weapon System Sustainment Management concept can be applied to achieve the goal of a leaner, more agile logistics system and that RAND-developed tools such as Dyna-METRIC and DRIVE may provide the basis for part of a standardized logistics management system.

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